NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION
TRANSACTIONS OF 1940

PART II
TWENTY-FIRST ANNUAL MEETING
APRIL 24 TO 27, 1940
WASHINGTON, D. C.

REPORTS AND PAPERS
GENERAL ASSEMBLY AND
SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY, TERRESTRIAL MAGNETISM AND ELECTRICITY, OCEANOGRAPHY, VOLCANOLOGY, HYDROLOGY, AND TECTONOPHYSICS

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
JULY, 1940

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

Annual assemblies of the Union and annual meetings of its Sections for the discussion of reports and for symposia are held each year. The first 13 assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C. Besides the annual general assemblies and meetings of each of the Sections held since 1933 in Washington, D. C., regional meetings of the Section of Hydrology were held at Berkeley, California (1933 and 1934), at Pasadena, California (1936), at Denver, Colorado (1937), at Spokane, Washington (1937), at Davis, California (1938), at Los Angeles, California (1938), at Spokane, Washington (1938), at Stanford University, California (1940), and at Seattle, Washington (1940). The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1928, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, sixteenth, seventeenth, eighteenth, nineteenth, and twentieth annual meetings were published in June 1931, June 1932, June 1933, June 1934, August 1935, July 1936, July 1937, August 1938, and July to August 1939, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, Part II of the "Transactions of 1940," also one of the miscellaneous publications of the Council, includes the proceedings of the twenty-first annual meetings held at Washington, D. C., April 24 to 27, 1940. [The proceedings of the regional meeting of the Section of Hydrology at Stanford University, California, January 12 to 13, 1940, including 29 papers and reports with considerable discussion, are published in Part I of the "Transactions of 1940."] At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The present volume (Part II) contains the 134 papers and reports, with duscussions, presented at the twenty-first annual meetings of the Union and its eight Sections at Washington in April 1940. As in the "Transactions of 1939," the minutes of the General Assembly and of those of the Sections, with their appendices, have been included following the proceedings of the Section of Tectonophysics. The total attendance of members and guests at Washington was in excess of that registered, namely, 551--a satisfying gage of the service of the Union to geophysics in the United States. The attendance at the regional meetings continues to emphasize growing interest in the United States in the activities of the Union's Section of Hydrology and in snow-surveying. Included in the minutes are the reports of officers and of standing, special, and research committees.

Six resolutions were adopted at the General Assembly. These related to the following subjects: Repositories for geophysical data; compilation and investigation of sounding data; seismological stations in the North Atlantic; seaward extension of submarine valleys; analysis and publication of data on rainfall and runoff; United States Naval Observatory time-signals.

The second award of the William Bowie Medal, endowed and established on March 1, 1939, for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics, was made to Dr. Arthur L. Day at the General Assembly of April 26, 1940. In the citation, reference was made to the eminence of Dr. Day's own personal researches, to his leadership of the foremost research laboratory in any country for the investigation of numerous geophysical and geochemical problems, and to his successful promotion of cooperative

effort in several different fields of geophysical research. Following the award of the Bowie Medal, there was a "Symposium on tectonophysics of the crust" in which were presented four papers on seismology and the first hundred kilometers of the Earth, on thermal measurements and their bearing on crustal problems, on deformation of rocks in the laboratory, and on the mountain-building cycle. The papers were followed by extended discussion.

At the session of the Section of Geodesy ten papers and reports detailed progress as follows: International Association of Geodesy; gravity-data and gravity-anomalies (3); astronomical observations and relations (2); tides; instrumental developments; and progress-reports on geodetic work in Mexico and the United States of America. There is included in this volume also one contributed paper on the basic gravity-survey of Cuba.

The Section of Seismology heard and discussed ten papers bearing on pressure-changes and earthquakes, seismic contributions to geology (2), accounts of individual earthquakes (2), methods of analysis (4), and instrumental developments. Besides these, five progress-reports were received.

The nine papers and discussions before the Section of Meteorology related to hurricanes (2), radiosonde technique, forecasts, circulation (3), and radiation-intensities.

The Section of Terrestrial Magnetism and Electricity heard and discussed 12 papers. These were concerned with geomagnetic tides, geomagnetic theory (3), geomagnetic prospecting (3), observatory at Rolla, Missouri, the ionosphere, atmospheric electricity (2), and solar vortices. Besides these papers, three progress-reports were received on magnetic activities.

There were presented before the Section of Oceanography four progress-reports of Federal and private organizations, two papers on circulation, one paper on internal wave investigations, and one paper on the Munch-Pederson formula.

Ten papers were discussed by the Section of Volcanology relating to volcanic formations and igneous rocks.

The Section of Hydrology held five sessions, one of which was a joint evening meeting with the Pick and Hammer Club. The 15 reports and three appendices of the Section's standing research committees and subcommittees indicated wide extension of hydrological research and applications. Besides these reports, 39 papers were presented, which may be roughly classified as follows: Salt-water intrusion (5), rainfall, runoff, and analyses (8), snow and glaciers (4), evaporation (2), infiltration (5), ground-water (5), stream-dynamics (9), and general research (1).

The first annual meeting of the Section of Tectonophysics was opened with a statement by President Field of the Union giving the reasons for the formation of this new Section. After election of officers, five papers were presented and discussed. These papers related to the physics of the Earth's crust as indicated by experimental work in the laboratory (3) and by geologic structure (1), and to experimental apparatus (1).

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of Sections. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, and contributions of money and of services from the Carnegie Institution of Washington, from the University of Nevada, from members of the Union, and especially from hydrologists both members and non-members. Each of the authors, except for a few who could not be reached, revised a carbon of the master-copy from which the "Transactions" were printed. The final master-copy was prepared by J. J. Capello and W. E. Scott, and was planographed by the Kirby Lithograph Company of Washington. Besides its obligation to authors, to members of committees, and to our colleagues in Canada and Mexico, who contributed to the twenty-first annual meeting, the Union is indebted to W. C. Hendrix for preparing many drawings of which the originals submitted were not suited for planographic reproduction and to P. G. Ledig and J. W. Green for photographic work.

Despite the nearly simultaneous outbreak of war in Europe and the unpropitious world political conditions, the Seventh Triennial General Assembly of the International Union of Geodesy and Geophysics was successfully held in Washington from September 4 to 15, 1939, as planned by the American Geophysical Union in collaboration with the National Research Council, and with generous contributions from the Federal Government through the Department of State, the Carnegie Corporation of New York, the Geological Society of America, the National Research Council, several scientific societies, and friends and members of the Union. This Assembly was the first to be held in the United States of America since the organization of the International

Union in 1919. An extensive exhibit of geophysical instruments, charts interpreting geophysical data, and models was a major feature of the Assembly. The exhibitors included interested Departments and Bureaus of the United States Government, American universities and research organizations, and American instrument-making companies. The American Geophysical Union exhibited a large series of charts showing the results of geophysical exploration as applied to continental and oceanic structure. It was the general consensus of opinion that the Seventh General Assembly will be numbered among the most successful and profitable which the Union has held. The exclusion of administrative matters and discussion pertaining to statutes and finance, which at some of the Assemblies have consumed much time, left greater opportunity for the presentation and discussion of scientific papers and reports.

Thus the American Geophysical Union, in the past year, has continued its service in forwarding the scientific and economic aspects of Earth physics and the coordination of International and National activities.

Jno. A. Fleming, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

GENERAL ASSEMBLY

SYMPOSIUM ON TECTONOPHYSICS OF THE CRUST

Washington, D.C.

April 26, 1940

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Symposium on Tectonophysics of the Crust

SEISMOLOGY AND THE FIRST HUNDRED KILOMETERS OF THE EARTH

James B. Macelwane

The seismologist is a peculiar being. He is one species of the genus geophysicist. Like other human beings he is curious about the Earth; but he is not so much interested in what is on the Earth or above the Earth as he is in what is in the Earth. The geologist is also curious about the Earth and he goes out to look. The geologist examines what he sees on the surface and what he can bring up with his probe called a drill. He works as it were with his eye, both aided and unaided. The seismologist, on the other hand, does not depend on what he can see; but he shakes the Earth and listens in order to find out what is inside. The seismologist therefore labors under many handicaps. He cannot go down inside the Earth any farther than can the geologist. He must listen from the outside. His ear may not be sufficiently sensitive or well attuned, and he may miss or mistake the import of the noises caused by the shaking. In fact, to change the metaphor, seismologists generally are left to feel around old mother Earth, and find themselves pretty much in the predicament of the blind men and the elephant, and they have often been betrayed into conclusions just as hasty and quite as unjustified from their inadequate evidence. This is one side of the picture.

On the other side is much that is encouraging. The seismologist undoubtedly has in his hands a very powerful tool for fathoming the depths of the Earth and discovering facts about its structure which are far beyond the reach of quantitative determination by any other method.

In the 15 years that have elapsed since seismic prospecting began in the United States on a large scale, wide stretches of territory have been explored and much of it repeatedly covered. As a result, knowledge of the structure of the first five kilometers of the Earth's crust has accumulated in the files of many commercial companies; but only a small part of it has been given to the public. The progress from 1929 when Heiland published his monograph up to the end of 1939 is striking; and the process of seismic exploration still continues in this country as elsewhere.

However, the structure that is revealed directly by seismic prospecting is confined almost entirely to the sedimentary layers. Indirectly we learn from it something of the configuration of the upper surface of the basement-complex, at least by inference. But of the other 95 per cent of our 100 kilometers seismic prospecting has told us nothing and probably can tell us nothing because of the inherent physical difficulties.

We, therefore, turn to the observation of natural earthquakes. Here again we meet with difficulties. In the first place, we have no control over the time or the place at which the earthquake will occur. We are, therefore, unable to use the techniques and equipment of seismic prospecting and we are forced to depend on the records of seismographs which have been designed for continuous recording with a much less open time-scale, much lower magnification, and no volume-control. Hence it is extremely difficult, if not impossible, to identify intracrustal reflections amid the welter of much larger waves. And even if this were possible they could not be used because of the inadequate accuracy of the time-scale. We should need to be sure of the successive arrival times to the nearest one-thousandth of a second; whereas, we are rarely certain of the nearest tenth of a second and the uncertainties usually add up to several seconds. Furthermore, the Earth seems to act as a filter and the observed wave-lengths of natural earthquakes are too long for the thickness of the crustal layers.

Our seismological knowledge of the first 100 miles, then, is primarily derived from the multiplicity of phases that are observed in the seismographic records of earthquakes in the neighborhood of the observing station, that is, at a distance of 100 to 500 miles.

This multiplicity of phases was first observed by A. Mohorovičić in the case of the Kulpa Valley earthquake of October 8, 1909--over 30 years ago. Longitudinal waves arrived at two different times at each observing station and so did the transverse waves. Moreover, the arrival times when plotted against distance determined two distinct but intersecting travel-time curves.

Mohorovičić interpreted these as the respective travel-time curves of a direct wave through the upper crust and of a wave refracted through the underlying subcrustal medium. On the basis of the observed travel-times Mohorovicić calculated the depth of the crust to be about 60 kilometers or 38 miles.

A little later Conrad found a third phase in the condensational waves of the Schwadorf earth quake of October 8, 1927, and in the Tauern earthquake of November 23, 1927. A corresponding transverse wave was found by Jeffreys in the records of the Jersey earthquake of July 30, 1926.

The assumption that the Earth's crust consists in general of layers separated by sharp boundaries affords an explanation of the various successive arrivals of longitudinal and transverse waves, respectively, on the records of near earthquakes. The fact that the first arrivals when plotted as times against distances from the epicenter tend to lie on a broken curve the successive segments of which, at least after the first and up to distances of several hundred miles, are straight lines is a strong argument in favor of the layer-hypothesis. So also is the continuation of these lines beyond their point of intersection with the next segment when later arrivals are plotted.

Four wave-kinematical hypotheses have been advanced to explain the mechanism of transmission of these later waves. First we had the refraction-theory of Wiechert and Gutenberg according to which the waves are refracted into the lower medium and at near critical incidence are recurved and refracted out again into the upper layer because of the increase of velocity with depth. This theory does not account for the relatively great energy possessed by these waves. Secondly, the normal-incidence-boundary-wave theory of some of the early seismic prospectors has very little in its favor and much against it. Thirdly, we have the diffraction or ground-glass theory of Jeffreys which is better than the refraction-theory but still inadequate; and lastly, we have the head-wave or traveling-reflection theory of von Schmidt. The last-named theory is derived from ballistics and seems to be the most reasonable of the explanations thus far offered for the relatively large amount of energy that is usually carried by these waves.

In any case the reciprocals of the slopes of the successive straight lines are the true velocities in the successive layers, since the time spent in traversing the overlying layers will be constant for all points on the given line and the increase of time with distance will be entirely due to travel in the lower medium near or immediately underneath the upper boundary.

Supposing the validity of the layering hypothesis, it should therefore be possible with a sufficient number of records of a given earthquake from nearby stations to locate the epicenter, to determine the thickness of the layers and the speed of longitudinal and transverse waves in each, and hence to find Poisson's ratio and the ratio of elasticity to density that is characteristic of each layer.

In the records of near earthquakes many phases have been identified by working seismologists. However, there is much disagreement concerning the interpretation to be put upon them. Jeffreys set up a generalized model crust of the Earth composed of two layers, an upper layer which he called granitic and a lower layer which he called basaltic. But his estimates of total thickness have varied through the years between 15 and 25 miles. In his latest paper Jeffreys seems to abandon hope of obtaining reliable thicknesses of surface-layers from the study of near earthquakes. He says "On the whole I think that the estimates of velocities are at the present stage the only useful information provided by near earthquakes" [Harold Jeffreys, Times of transmission for small distances and focal depths, Mon. Notices R. Astron. Soc., Geophys. Supplement, v. 4, p. 576, 1939]. Gutenberg sought to reconcile his own findings and those of Mohorovičić for southern Europe with those of Jeffreys by supposing the latter held primarily for northwestern Europe and the British Isles and that the lower boundary of the Earth's crust sloped upward from the Alps to the North Sea. Gutenberg's interpretation has at least this plausibility that studies of surface-waves seem to indicate a thinner crust under the oceanic basins than under the continents. And the latest results seem to indicate that the floor of the Atlantic Basin is similar to that of the Pacific Basin.

It is the writer's opinion that crustal structure is a local problem and that we have no warrant in the observations thus far made to generalize any particular structural layering or thickness of the crust over the whole Earth or even over any major portion of it. Our observations thus far of course are only qualitative; but, as far as they go, each individual locality seems to have a structure of its own.

Gutenberg and Richter found a many-layered structure in California and a total thickness of more than 20 miles. Hodgson found for Japan and Bullen for New Zealand a relatively simple structure, an almost complete absence of the continental or granitic layer and a total thickness less than ten miles. In New England, Leet and others find the structure to be quite different from either. In the Mississippi Valley the crust seems to vary in different directions from the Ozark Uplift and again it seems different from either New England or California.

Less definite are the indications for the material below the crust. The behavior of the transverse waves at distances corresponding to this depth of penetration seems to be anomalous and is not yet understood. Much work remains to be done before seismologists will be in a position to make any positive statements concerning the subcrustal shell. The problem is complicated by the fact that earthquake-waves through this shell cannot be observed without having passed through the crust and being modified by the crustal structure. Waves from shallow earthquakes will in general have passed through two different structures, the one at the focus and the other at the observing station. In the case of earthquakes which have originated, as many of them do, in the subcrustal medium anywhere between the Mohorovičić discontinuity at the base of the crust and the arbitrary 100-kilometer level assigned to us, one of the passages through the crust is, of course, eliminated and the waves will have been affected only by the subcrustal medium and by the crustal structure at the station. This is more likely to be known in any given case than are the conditions at the focus.

In conclusion, I would say that seismology is in a better position, perhaps, than other sciences to offer plausible suggestions based on observation concerning the make-up of the first hundred miles; but it is not able as yet to present a blue-print plan based on adequate data and thoroughly reliable measurements.

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THERMAL MEASUREMENTS AND THEIR BEARING ON CRUSTAL PROBLEMS

A. E. Benfield

In opening the thermal part of this symposium I want to say a little about terrestrial heat-flow, that is, the amount of heat which flows from the interior of the Earth and comes to its surface. We know at present very little about this quantity. Yet, if we are interested in calculating what temperatures exist at depths in the Earth greater than those which we can reach with a drill, it is necessary to know, among other things, how great this heat-flow is. Later I shall mention some particular geophysical problems where heat-flow measurements can give us information.

If a temperature-gradient, p, exists at some region in a body where the thermal conductivity is k, then the amount of heat per unit-area per unit-time which flows across a surface normal to the temperature-gradient is

$$H = - k p$$

In order to find H it is necessary to know both p and k. If, therefore, we wish to determine how much heat is flowing to the surface of the Earth, we can do so by measuring temperature-gradients and conductivities near the surface.

It is most important to measure both these quantities at the same place. For many years experiments have been made to determine the thermal conductivities of rocks, and for a long time temperatures have been measured in wells, tunnels, and mines, but there are very few places on the Earth where both the temperature-gradients and the conductivities are known. As the value of k for different rocks varies through a factor of 20 or more, and as p in one region may differ by a factor of six from that in another district (neglecting hot-spring and volcanic areas), the practice of estimating the heat-flow by taking "average values" leads to a very uncertain value of H, and gives us no information at all about how the heat-flow may vary from one part of the Earth's surface to another.

Table 1 shows some past estimates of H and, below them, heat-flow values deduced from temperature-gradient and rock-conductivity measurements made at the same place. The two columns, surface-flow and equilibrium-flow, which appear under "measured values" in this Table should be explained. The surface-flow is the actual amount of heat flowing to the surface at the present day, while the equilibrium-flow is the amount which would now be coming to the surface if there had not been any geologically recent change in the mean surface-temperature, such as that caused by the withdrawal of an ice-sheet at the end of an ice-age. Except for a somewhat uncertain value of the heat-flow for the Simplon Tunnel Region, the measured values shown in Table 1 are, as far as I am aware, the only ones that exist.

The heat-flow values for the Calumet and Hecla Mine have been calculated by combining the

Table 1--Estimates of H and heat-flow values

	H x 10^6 cals/cm^2-sec	Surface-flow	Equilibrium-flow
Some past estimates			
Joly	3.45		
Jeffreys	2.56		
Anderson	2.0		
British Association	1.63		
Measured values for			
Michigan			
Calumet and Hecla	....	0.6	0.8
South Africa			
Jacoba	....	0.96	
Doornhoutrivier	....	0.97	
Gerhardsminnebron	....	1.28	1.16 (±0.09) 1.16±0.09
Doornkloof	....	1.20	
Reef-Nigel	....	1.03	
Dubbeldevlei	....	1.52	
Britain			
Balfour	....	0.68	
Holford	....	0.74	
Blythswood	....	1.24	0.98 (±0.17) 1.42±0.14
South Balgray	....	1.53	
Hankham	....	0.71	

temperature-measurements of L. R. Ingersoll and others [see 1 of "References" at end of paper] with some conductivity-measurements made by B. O. Peirce [2] almost 40 years ago on rocks from this mine. The South African values are the result of some very good work done recently by E. C. Bullard [3] and L. J. Krige [4] in deep wells in that country. The heat-flow value for each well is shown in Table 1, and also the arithmetic mean of the heat-flows in the six wells, together with the standard deviation of this mean. The British values have been calculated from conductivity- and temperature-measurements made by myself and others for various wells in Britain [5].

Ingersoll found an increase of the temperature-gradient with depth and from this deduced a date for the withdrawal of the Quaternary ice-sheet from the Calumet and Hecla Mine District. Using this date one can calculate an equilibrium heat-flow of about 0.8 x 10^{-6} cal/cm^2-sec for this district. This value is somewhat uncertain. In Britain there is also some evidence of an increase of heat-flow with depth. Although the wells were not deep enough to assign with any accuracy a date for the withdrawal of the ice-sheet, a rough value of about 9,000 B. C. seemed to be indicated, and the equilibrium heat-flow values have been calculated using this date, leading to a mean value for the five wells of 1.42 x 10^{-6} cal/cm^2-sec with a standard deviation from this mean of 10 per cent. In South Africa no evidence was found of a change of heat-flow with depth such as could be attributed to climatic changes, and so in that region the surface and the equilibrium heat-flow values are identical.

It is interesting and important, I think, that the past estimates of the average heat-flow are higher, some of them very considerably higher, than the measured values. With so few measured values it is too early to assume that the heat-flow is generally low, but it is interesting to consider what a low heat-flow value might imply, and I shall say more about this later.

I should now like to say a few words about the experimental method which Bullard and I have used to obtain these values. The temperature-gradient data were secured by making temperature-measurements in wells or by making use of the careful temperature-measurements of others. The conductivities were determined from measurements in a laboratory on specimens cut from representative rock-cores taken either from the well under investigation or from nearby wells piercing the same strata. The method we have used is the divided-bar method, and the type of apparatus is shown in Figure 1. As this method is well known, I shall not say much about it. In this apparatus heat is generated electrically at the top of the metal rod A, flows down through this rod and through the rock specimen R, and on through the lower metal rod B, at the bottom of which it is finally carried away by the water-cooling. By taking into proper account the temperature-drops at the two rock-metal interfaces, conductivities over a wide range of values can be reliably determined with little trouble.

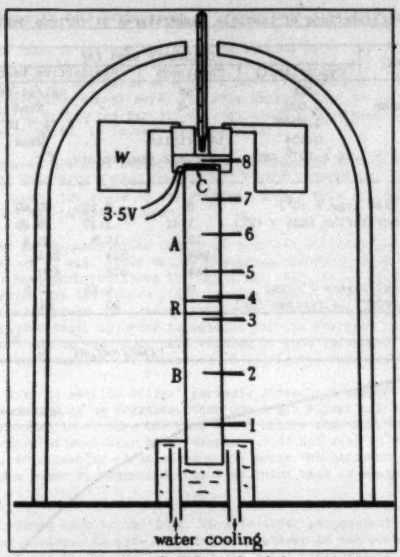

Fig. 1--Diagram of rock-conductivity apparatus

It would seem, perhaps, to be more satisfactory if conductivity-measurements could be made in situ, that is, without removing the rocks to a laboratory, but to do this all the way down a deep well would involve a number of difficulties. Bullard and I have investigated the various possibilities of errors in our conductivity-determinations due to the removal of the rocks from their natural positions, and we do not believe that, with the precautions taken, this procedure introduces any appreciable error.

Table 2 and Figure 2 show the results of some calculations of possible temperatures at depth. For the purpose of these calculations three layers were assumed to exist, an upper or sedimentary layer, underneath which is a granitic layer, and finally deeper still a lower (basaltic) layer which is considered to extend indefinitely downward. Furthermore, it is assumed that the amount of radioactive heat generated within the Earth is not more than the amount flowing to the surface, and that all the radioactivity is confined to the granitic layer.

The values given in Table 2 above the dotted line are the constants used, and the figures below it (with the exception of the first row) are those deduced from them. A low heat-flow value implies correspondingly low temperatures at depth, and in order to try to remedy this I have assumed a sedimentary layer six km thick having the low conductivity of 0.003 cgs, and the low conductivity of 0.004 for the basaltic layer. Besides, I have taken the highest of the equilibrium heat-flow values (1.42×10^{-6} cal/cm^2-sec) and, as already mentioned, I have assumed that no radioactivity exists below the granitic layer.

The first row of figures below the dotted line gives four assumed values of the residual heat-flow, that is, the amount of heat reaching the surface due to the Earth's secular cooling. The second row gives that amount of heat reaching the surface due to radioactivity. Each column of these first two rows, when added together, gives the total heat-flow at the surface (1.42×10^{-6} cal/cm^2-sec).

The third row gives s, the thickness of the granitic layer, which is calculated by assuming a radioactive heat-output of 0.74×10^{-12} cal/cc-sec for this layer; and the fourth and fifth

Table 2--Calculations of possible temperatures at various depth

Layer or item	Constants used for				
	Conductivity	Thickness	Radioactive-heat output		
	cgs	km	cal/cc-sec		
Sedimentary layer	0.003	6	None		
Granitic layer	0.0068	s	0.74×10^{-12}		
Lower layers	0.004	indefinite	None		
$H = 1.42 \times 10^{-6}$ cgs		Surface-temperature, 0°C			
Residual heat-flow (cgs $\times 10^{6}$)		0	0.25	0.50	1.05
Radioactive contribution (cgs $\times 10^{6}$)		1.42	1.17	0.92	0.37
s (km)		19.2	15.8	12.4	5.0
T_{SG} (°C)		284	284	284	284
T_{GL} (°C)		484	478	460	375
Gradient in lower layers (°C/km)		0	6.25	12.5	26.2
Depth at which 900°C is reached (km)		...	90	54	31

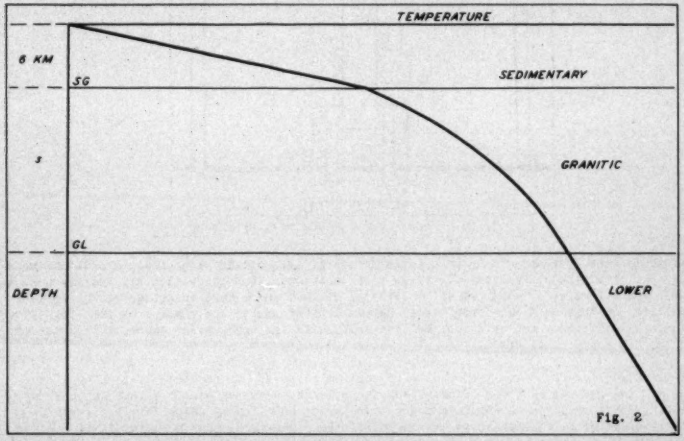

Fig. 2

rows give the temperatures at the bottom of the sedimentary and granitic layers respectively (T_{SG} and T_{GL}). The sixth row gives the temperature-gradient in the lower layer, and the seventh the total depth below the surface at which 900°C would be reached if one were to extrapolate the gradient in the sixth row.

The value used for the radioactive-heat output of the granitic layer is probably too high. As a result of some recent work a value of about 0.50×10^{-12} cal/cc-sec (that is, only two-thirds as high as the figure I have taken) is more likely to be correct. This lower value will have the effect of increasing the thickness, s, of the granitic layer to 3/2 of the value shown in Table 2 and Figure 2, and of increasing the temperature at its base (T_{GL}) by 45° C to 100° C.

I should now like to mention some geophysical problems which heat-flow measurements can help to solve. I have already mentioned the possibility of dating the last ice-age. Heat-flow measurements might also be able to help to explain the cause of glaciation. One ice-age theory, the Croll Theory, attributes glaciation to a change in the ellipticity of the Earth's orbit, while another theory postulates a change in the solar constant. There are some difficulties in the former theory, but if it were to be true, then glaciation should occur alternately in the Northern and Southern hemispheres of the Earth, whereas if the latter theory applies the ice-

ages would be simultaneous in both hemispheres. Further heat-flow measurements might help here.

Another problem is that of whether the Earth is warming up or cooling down. There are some people who believe that more heat is generated by radioactivity within the Earth than reaches the surface, and if this is so the Earth as a whole must be warming up. Heat-flow measurements alone cannot give us a definite answer here, for this depends also on our knowledge of the distribution of radioactivity within the Earth. But, although a knowledge of the heat-flow is not sufficient to decide this point, it is certainly necessary.

Heat-flow measurements are also connected with the question of volcanoes. It has been calculated by Anderson [6] that with a heat-flow of 2.2×10^{-6} cal/cm^2-sec the temperatures at the bases of his basaltic layers are close to the melting point. This no longer holds when a heat-flow value of 1.4×10^{-6} cal/cm^2-sec is used.

With regard to the Earth-contraction theory of mountain building, low heat-flow values would suggest two things. First of all, other things remaining the same, more cooling and therefore more contraction would have occurred since the Earth was born, which seems at first sight to favor the theory. However, in the second place, a slow present rate of cooling suggests that less contraction occurred between the late Paleozoic and Tertiary mountain-building cycles. Anderson [7] has calculated that, in order to account for the observed folding, a residual heat-flow of about 2.5×10^{-6} cal/cm^2-sec must have existed in this interval. A total heat-flow value as low as 1.42×10^{-6} cal/cm^2-sec introduces a difficulty for this theory.

Finally I should like to mention Griggs' periodic convection-current theory [8]. If the Pacific is a convecting cell, as he suggests, then one might expect the material under the western side of this country to be some 300°C to 400°C hotter than that under the Appalachians, and this might be detected by heat-flow measurements. I do not wish to say that a high heat-flow in the western part of this country would necessarily prove the existence of the convection-cell, as other interpretations might be suggested, but I do think that it would be an interesting matter to investigate.

In conclusion, I should like to say that, as with other geophysical methods, heat-flow work may not by itself be able always to give us a definite answer to our problems, but it is capable of providing us with additional information which may be of considerable value.

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DEFORMATION OF ROCKS IN THE LABORATORY

David Griggs

Introduction--In the search for understanding of the causes of deformation of the Earth's crust, it is particularly important to know two physical properties of the rocks constituting the crust--properties which are analogous to strength and viscosity as measured in engineering testing laboratories. Experiments on the deformation of rocks show that neither of these is a simple or easily defined property. In the following, "strength" will be used rather loosely as the stress which causes rupture under specified conditions. "Equivalent viscosity" will be used to describe the flow of rocks under constant stress. It is a term which is derived in the same manner as ordinary viscosity of liquids, but different in that it varies as a function of the applied shear-stress.

Geological observations provide evidence as to the order of magnitude of viscosity of the substratum and strength of the continental crust. The former, derived from the return of the

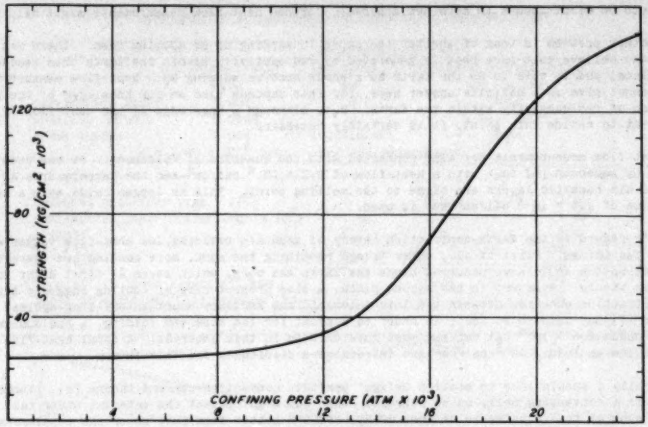

Fig. 1--Strength of quartz single crystals cut parallel to the "c"-axis as a function of confining pressure

Earth's crust after depression by the load of the glacial ice-caps, is of the order of 10^{22} poises, expressed as equivalent viscosity measured under an average stress of the order of 10 kg/cm^2. The latter is of the order of 1,000 kg/cm^2, derived from the local departures from regional isostasy which are thought to be borne by the strength of the crust.

Since both of these figures necessarily rest on somewhat controversial assumptions, it is important that we seek the independent confirmation which experiments in the laboratory may provide. Of similar importance is the unexpected information which the experiments give us as to the nature of flow and strength.

Strength and equivalent viscosity vary as functions of all five of the environmental variables in the Earth's crust, and an experimental approach to the determination of these two properties must determine first the effect of varying each variable separately with all the rest held constant, and then the effect of simultaneous variation of combinations of the variables. These variables are:

(1) Confining (hydrostatic) pressure
(2) Temperature
(3) Time
(4) Solutions
(5) Shear-stress

The last of these cannot be treated as an independent variable, since shear-stress is necessary in all experiments to investigate properties of strength and flow.

The effect of confining pressure--Confining pressure alone greatly increases the strength of all the materials which have been tested to date. In all cases, however, the strength increases only slightly until a certain critical pressure is approached (apparently characteristic of the mineral components and not the state of aggregation), when the strength rises very suddenly. In all the writer's experiments, this increase has continued to the limit of experimentation. Bridgman's shearing experiments, on the other hand, suggest that at higher pressures the strength may approach some limiting value, beyond which continuous flow takes place.

Before the Section of Tectonophysics, Goranson presented a thermodynamic analysis of the strength-pressure relationship. His conclusion is that at a critical pressure for each material the strength will increase to infinity. His strength-pressure relationship, calculated from free-energy considerations, is of the same form as that experimentally observed. It must be borne in mind, however, that Goranson's theory refers to stress required to produce fracture, and is not applicable to flow in its present form.

Typical of rocks under high pressures is the form of the strength-pressure curve of quartz, shown in Figure 1. This is different from most, however, in that the strength is at all times higher than usual for the rock-forming minerals, and its maximum strength has never been approached in tests with other minerals, though perhaps only because the experimental conditions have been inadequate in other mineral tests. The experiments which provide the data for Figure 1 have been performed in three different types of apparatus. The value at 12,000 atmospheres was accurately determined with the specimen surrounded by liquid under constant pressure. The other points, with the exception of the last one, were obtained in a more inexact apparatus in which the specimen was surrounded by lead. The highest value was determined by Bridgman, in his newest apparatus in which the specimen was surrounded by liquid at a pressure determined by the transition of bismuth, and therefore held sensibly constant at 24,000 atmospheres.

The effect of pressure on equivalent viscosity of rocks has not been adequately determined, except for the single case of alabaster surrounded by water, which will be described later. The equivalent viscosity is a strong function of the magnitude of the shear-stress, and hence one may compare only values measured under the same shear-stress or else compare the functional relationship between shear-stress and velocity of flow at different values of confining pressure. Only one set of experiments has been done with this in mind--a series of creep-tests on Solenhofen limestone at 10,000-atmospheres confining pressure. These were performed at values of shear stress much higher than the strength of the limestone at low pressures, so it is impossible to obtain correlative values at low pressure. It may be said in passing, however, that the equivalent viscosity at 10,000 atmospheres and under a shear-stress of 2,125 kg/cm^2 is less than one millionth of that under no confining pressure and a shear-stress of 700 kg/cm^2.

The effect of temperature--Temperature alone produces unimportant effects in those rocks and minerals with which the writer has experimented, but both the precision of the measurements and the number of materials investigated leave much to be desired. At present one can only say that temperatures as high as one may expect in the outer 30 km of the crust produce very much smaller changes than pressures in the same range.

The effect of time--Creep-experiments in which a specimen is subjected to small shear-stresses held constant over a long period of time and the deformation is measured very accurately, have shown that many materials exhibit continuing flow under stresses smaller than their nominal "elastic limit". In all the rocks investigated under no confining pressure, and in the dry state, however, the velocity of flow decreases inversely in proportion to the time, hence rapidly becoming so small that measurement is difficult. Further, in every case where measurement of flow on release of load has been measured, it is found that this flow is reversible, which is to say that in an interval of time equal to that of the stress-application, the specimen will return to its original dimensions. This so-called "elastic flow" would appear, therefore, to be unimportant in geological problems.

An experiment on Solenhofen limestone provides the best illustration of the effect of time alone on rock-flow. This specimen, under a shear stress of 700 kg/cm^2 (normal breaking strength about 1,000), at room-temperature and pressure, and in a room where the humidity was maintained at a low value, exhibited only elastic flow over a period of more than three years, and the minimum equivalent viscosity for any pseudoviscous flow which escaped detection could be only 2×10^{22} poises--more than twice the viscosity as calculated from yielding of the substratum under a shear-stress only one-hundredth as great. If similar behavior were to be found in rocks under environmental conditions similar to those deep in the Earth, it would support the contention that the rocks of the crust are strong and unyielding, compared to the substratum.

The effect of solutions--When alabaster is tested in creep as above, it exhibits only elastic flow of very small magnitude. When, however, it is surrounded by a small jacket of its own saturated aqueous solution, it deforms first rapidly, gradually decreasing to an equilibrium state of pseudoviscous flow, and then, if the stress is high enough, accelerates continuously until fracture occurs. It is found that the velocity of pseudoviscous flow varies with the stress as follows:

$$v = A \sinh B(\sigma - S)$$

(v = velocity, S = fundamental strength, σ = stress, A and B are empirical constants).

This behavior under conditions of solution and recrystallization was predicted some years previously by Goranson, but he did not publish it for lack of experimental corroboration. The writer independently derived the above equation, and then found that not only it, but other factors in the behavior of alabaster under conditions of recrystallization flow were predicted by Goranson's earlier work.

For comparison of pseudoviscous flow under different confining pressures, that part of the curve in which the stress is considerably in excess of the fundamental strength is chosen. Here the above equation reduces to

$$v = (A/2)\, e^{B(\sigma - S)}, \quad \text{or} \quad \log_n (2v/A) = B(\sigma - S)$$

Goranson predicted that the slope of the $\log_n$ v-versus-σ curve (constant B in the equation) would be reduced by a factor of 1.5 when similar tests were made under a confining pressure (supplied to the specimen by the solution) of 1,000 kg/cm^2. In the writer's experiments the observed factor was 1.55, providing further verification of Goranson's theory. Reflection will show the reader that this means that the equivalent viscosity of this recrystallization flow is much lower under the increased confining pressure.

Experiments on other materials, such as marble, show that recrystallization flow of any considerable magnitude does not occur under similar testing conditions--presumably because of the much lower solubility of the calcite. When, however, by elevation of the temperature, coupled with increased confining pressure, the solubility is increased, then flow is greatly facilitated. In this broad field, experimentation is difficult and the techniques complicated. The writer is concentrating on the development of apparatus and exploration of this phase of the work, in which all five of the environmental variables are duplicated to a moderate degree.

New experimental results--With the aid of a project-grant from the Geological Society of America, apparatus has been constructed in which it is possible to maintain high temperature, moderate pressure, and high shear-stress in any desired chemical environment for periods of months. Preliminary experiments indicate that this combination of variables will produce effects hitherto impossible. For example, quartz, which has resisted all previous attempts to produce any considerable plastic deformation in it, under the new conditions is highly mobile and moves around more freely than calcite. A quartz-sand, surrounded by distilled water under 1,000 atmospheres pressure, at 400° C, and under a shear-stress of 2,000 kg/cm^2 becomes a hard quartzite in two days. This quartzite exhibits all the gross physical properties of true quartzite, and the microscope shows that individual grains have dissolved at points of contact and cemented themselves together producing the texture of a typical quartzite.

A further line of experimentation which has not previously been reported on is the recent work of James Balsley and the writer investigating the properties of marble in "tension" under high confining pressure. In these experiments, a marble cylinder is placed under uniform hydrostatic confining pressure, and then the pressure along the axis is lowered, producing a stress-system similar to that of tension in the testing laboratory. Although all the stresses are compressive, the specimen breaks with a typical tensile fracture normal to the direction of least pressure. Contrary to previous tests in tension, the marble shows marked ductility, and extensions up to 22 per cent have been measured before fracture occurred. Another curiosity of these tests is the great dependence of strength, or resistance to flow, on the orientation of the calcite crystals. When the crystals are so oriented that twinning takes place most readily, the resistance to flow is only half that when the crystals are oriented at right-angles to this direction.

Conclusions--The experimental evidence in hand is insufficient to provide a quantitative value for either the strength or the equivalent viscosity of the rocks of the Earth's crust. It does seem to indicate, however, some important phenomena in this connection. Most important of these is the pseudoviscous behavior of rocks under stress. In all the tests under widely different conditions, this pseudoviscous behavior, from which an equivalent viscosity is calculated, differs from ordinary viscosity in that the velocity of flow increases not in direct proportion to the shear-stress as in true liquids, but exponentially with the stress.

From purely empirical evidence the prospect is not bright for the attainment of such values of strength and equivalent viscosity as we desire in tectonophysics. When, however, we understand the basic theory of deformation, then, with adequate experimental determination of the empirical constants, we may estimate with confidence the behavior under all conditions in the outer shells of the Earth. Goranson's theory of deformation is already adequately confirmed by experiment to give us confidence in such calculations which may ultimately be derived from it.

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THE MOUNTAIN-BUILDING CYCLE

Walter H. Bucher

The preceding papers have set forth characteristic aspects of tectonophysics, that is, the concerted effort to understand the structural details of the Earth's crust and the physical condition of the Earth as a whole in terms of the modern physics of materials. On the geophysical side, this effort comprises two main lines of work: (a) The determination of the present physical condition of the Earth's surface and its body as a whole, through measurements of as many variables as possible at as many points on the Earth as possible; (b) experimental determination in the laboratory of the laws of deformation of the materials and the necessary constants involved.

On the side of geology, tectonophysics demands a critical, accurate description of structural detail as well as of the structural features of the Earth in their larger relations. Compared to the geophysicist, the geologist is at a great disadvantage. Whereas the former observes a present condition or behavior, the latter must decipher the overlapping and fragmentary records of successive stages of behavior. While the former measures the time-dimensions by means of radio signal, stop-watch, or clock, the latter has only a few relatively crude, indirect methods by which to determine the incidence in time, measured by tens of millions of years, of successive structural events.

Yet it is largely the geologist who must furnish the essential data which define the nature of the physical processes that have produced the present structure of the Earth's crust. The goal of his efforts must be a picture accurate enough to permit the mental construction of a model Earth from which not only the present distribution of physical properties, including the distribution of major stresses and strains, may be deduced, but the long sequence of former states of which the present tectonics of the Earth's crust are the visible record. Every informed geologist knows that the sum total of knowledge sufficiently accurate for that purpose is as yet wholly inadequate, even as far as the essential structural features of a relatively well-known country like the United States are concerned. We must be content, therefore, for a long time to come with thinking in terms of partial hypotheses that must be checked constantly against the growing stock of accurate information.

The topic assigned to the speaker, "The mountain-building cycle," occupies the center of all thinking concerning the dynamics of the Earth's crust. It refers specifically to the cyclic recurrence of tangential movements accompanied by more or less intense deformation along the long and relatively narrow orogenic zones which are a unique feature on the face of the Earth. It is the purpose of this comment to point out emphatically that any attempt to find an explanation for this cyclic phenomenon, in order to be successful, must take into account what goes on outside the orogenic belts. The "cycle of mountain-building" is but one aspect of a greater cyclic process that affects all parts of the Earth's crust.

We turn, accordingly, from the spectacular phenomena of the orogenic belts to the large surfaces that lie between them. There another cycle is clearly recognizable. It consists of alternating transgressions and regressions of the sea. Grabau has assembled a large amount of stratigraphic data that seems to bear out the inference that, in spite of divergent local conditions, the broader phases of this cycle are essentially world-wide (pulsation-hypothesis). The epochs of regression outside the orogenic belts coincide with regression and orogenic movements within them. Similarly, periods of transgression outside coincide with transgression of the sea and absence of orogenic movements inside the orogenic belts. The "mountain-building cycle" is thus but a part of the diastrophic cycle of the Earth's crust.

The transgressions and regressions of the sea result from changes in two variables, namely, (a) the volume of water in the oceans, and (b) the dimensions of the space that lies below sea-level. As far as the speaker knows, there is no reason to assume that the volume of water in the oceans has undergone changes of significant magnitude, at least during the time-invervals involved in the cycles of transgression and regression with which we are concerned in this discussion. For the purposes of this argument we shall, therefore, assume that the volume of water remained practically constant.

The amount of space that lies below sea-level depends on the relative position of sea-level. This can be changed in two ways: (b) By deposition of sediments below sea-level; (b) by crustal deformation. While it is impossible, at present, to arrive at any convincing estimate of changes in sea-level produced by sedimentation below sea-level during a given time-interval, a consideration of the geological facts leads to the conclusion that the changes of sea-level due to sedi-

mentation are of a smaller order of magnitude than those produced by crustal deformation and may, therefore, be neglected in a qualitative analysis of the nature of marine transgressions and regressions. The facts are as follows:

Whenever, in the accessible geologic record, the sea transgressed over parts of the interior of a continental mass, the continental surface did not merely become submerged as, for example, that of North America would be, if its whole surface were lowered uniformly say 1,000 feet. Instead, lowering centered over one or several areas forming basins of sedimentation. In the typical cases, sedimentation even in the central parts of the basins took place in relatively shallow water, generally hardly more than one or a very few hundreds of feet in depth. But sediments have accumulated in such basins, in the course of three or four geologic periods to thicknesses of one to several thousand feet depth. This shows conclusively that the surface of the basins was actively lowered not only with reference to sea-level, but to the surrounding lines of swells. The nature of this shortening of the Earth's radius beneath the basins is one of the fundamental problems of crustal deformation.

The lines of swells that separate the basins do not rise with reference to sea-level while the basins sink. In typical cases they receive sediments also, at least during the advanced stages of transgression, so that on them the sedimentary record is fragmentary, representing only a part of the sediments in the basins and that partly at least in reduced thicknesses. The lines of swells between the basins are, therefore, merely belts of lesser lowering with reference to sea-level, but nevertheless of actual lowering. American geologists are familiar with these relations along the lines of swells that characterize the structure of the eastern half of the United States, such as that of the Jessamine and Nashville domes, and the Mississippi arch and Ozark domes. The Paris and Aquitanian basins of Mesozoic-Cenozoic age in western Europe are especially instructive. They represent portions of the but recently peneplaned surfaces of the Late Paleozoic orogenic belts. The contrast between the peneplaned strongly linear belts of folding that emerge in the "swells" of Brittany, the Plateau Central, and the Rhenish uplift on the one hand and the non-linear broad basins that cut across them, on the other, is shown strikingly on the geological map of France. It should be studied carefully by anyone concerned with the problem of crustal deformation.

During times of regression, the roles are reversed. While both, basins and swells, rise with reference to sea-level, it is the swells that rise differentially with reference to the basins. The result is that they rise above sea-level and, in the typical case, have hundreds of feet of sediments removed from them by erosion. In the basins, on the other hand, there may be only a slight stratigraphic hiatus followed by rapid sedimentation. The Late Middle Devonian and the Late Mississippian deformations in the eastern half of the United States, which were followed

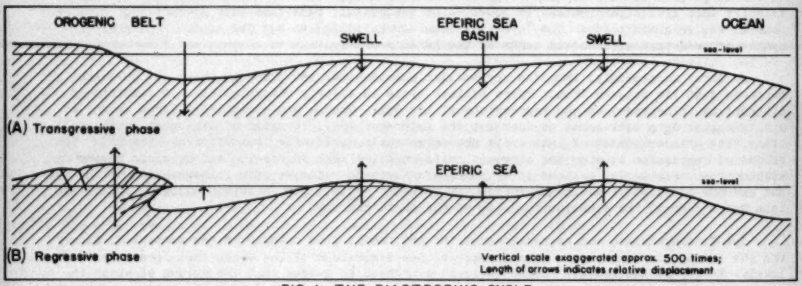

FIG. 1—THE DIASTROPHIC CYCLE

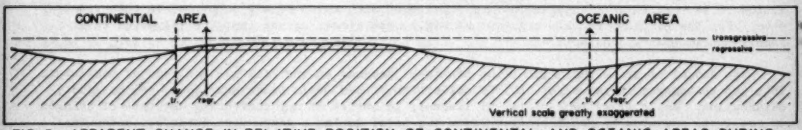

FIG. 2—APPARENT CHANGE IN RELATIVE POSITION OF CONTINENTAL AND OCEANIC AREAS DURING TRANSGRESSIVE (tr.) AND REGRESSIVE (regr.) PHASES OF DIASTROPHIC CYCLE

by the transgressions of the Upper Devonian Black Shales and the Pottsville, respectively, are familiar examples.

In the swells, these epochs of regression represent true deformation, accompanied by steepening of dips across which later sediments come to lie with regional unconformity. They coincide with epochs of folding in the orogenic belts. To the speaker, the conclusion seems inevitable that outside as well as within the orogenic belts, active compression prevails in those phases of the diastrophic cycle which are represented by epochs of folding and thrusting in the orogenic belts. The opposite phase during which in the orogenic belts, in the most typical cases, thick series of limestones or radiolarites or very fine-grained marine shales accumulate in complete conformity, that is, in absence of any evidence of tangential movements, obviously is the exact counterpart of that which causes essentially continuous sedimentation in the basins.

In both the transgressional and the regressional phase, the difference between the behavior of the crust inside and outside the orogenic belts seems to be quantitative rather than qualitative (Fig. 1). In the same time-interval, the surface of the Earth is depressed deeper along the elongated mobile belts than in the more or less equidimensional basins; and in the orogenic phase uplift and deformation are greater along the sharply defined orogenic belts than along the ill-defined lines of swells between the basins.

These relations have been tested with some care only in Europe and North America. Even there, studies in sufficient detail are available only for a few basins and swells. It is but hypothesis when we assume these conditions to be typical of all land-masses. Yet as far as the writer knows, similar conditions seem to prevail in the other continents. Without concrete evidence of essentially different conditions elsewhere, no other hypothesis seems acceptable at the present.

The little that is known so far concerning the larger features of the topography of the ocean-floors points to similar structural conditions. On the floor of the Atlantic, the best-mapped of the oceans, the mosaic of basins separated by lines of swells is a conspicuous feature. The contrast between them and the West Indian orogenic belt, with its island-chains and submarine welts and furrows, is as striking as any seen on land. Everything suggests that the processes which operate on the exposed parts of the Earth's crust act also on the twice larger area of the ocean-floors.

This raises a significant question. How can the non-orogenic phases of the diastrophic cycle, which comprise the larger part of geologic time, be times of marine transgression if in their course the structural basins on the ocean-floors, which are more numerous and much larger than those on the continental surfaces, are deepened relative to the surrounding swells like those on land?

The speaker believes the most probable answer to be, that the relative vertical distance between the continental and oceanic surfaces decreases during the non-orogenic phase and increases during the orogenic phase. This is expressed in Figure 2 by arrows which indicate relative movement.

The answer may, however, be simpler. The volume of the ocean-basins need be increased by the lowering of the floors of the numerous structural basins beneath the oceans only if the framework of the intervening swells remains fixed in its vertical distance from the center of the Earth. It is possible, however, that basins are merely lowered differentially with reference to the Earth's surface of which every point is actually being lowered as the result of a general shrinkage. The volumetric changes involved in a slight shortening of the radius of a sphere are so great that it is entirely possible that a local increase in depth is more than offset by loss in total area.

For the purposes of this symposium it is not desirable to follow this trend of thought. It is hoped that the main thesis has been brought out clearly. The diastrophic cycle is a matter of the whole Earth's crust, of which the cycle of "mountain-building" is only the most spectacular expression.

The speaker is convinced that this cycle, in its most general terms, may be defined as follows. It consists of alternating non-orogenic and orogenic phases. The non-orogenic phase is characterized on the continents by sinking of parts of the Earth's surface below their former position (with reference to the center of the Earth), this sinking being least along the lines of swells, greater in the centers of the basins, and greatest along elongated belts within the orogenic zones. The orogenic phase consists of a rising of parts of the Earth's surface above

their former position (with reference to the center of the Earth), this rising being least, or zero, or possibly even negative, in the centers of basins, greater along the lines of swells, and greatest within the orogenic zones where it is accompanied by more or less conspicuous tangential movements and resulting deformations.

It is the task of the structural geologist to test the correctness and generality of this picture and to refine it in its details. In so far as he has confidence in the validity of this picture, the geophysicist then will bring his ingenuity to bear on the problem of its possible meaning in terms of the physics of materials.

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Discussion

(1) Seismology and the first hundred kilometers of the Earth

JOHN N. ADKINS--Six major quarry-blasts obtained in L. B. Slichter's program of blast-observation in New England have been studied. Three occurred south of Albany, New York, and three near New Haven, Connecticut. The blasts are recorded on 12 specially designed portable seismographs which are set up throughout New England before each blast. Each instrument records three components of motion on photographic film. Time is marked simultaneously on all records every second by radio. Accuracy of the observations is increased by using an extended time-scale

In the study of the records, valid impulses are verified and spurious ones eliminated by comparison of the records of two distinct blasts from the same quarry recorded at the same observation-station. The data from the blast records have been used to compute the crustal structure of New England.

[Slides of observation-stations, typical records, travel-time curves, and deduced structure were shown.]

J. T. WILSON--The dispersion of surface-waves offers a means of calculating crustal structure. However, as the results are not very precise, it is best used where other methods cannot be applied. The dispersion of surface-waves has been used by a number of workers to determine crustal structure, and it was primarily from such data that the difference between the Pacific and continental regions was determined. Material of high velocity being much nearer the surface beneath the Pacific, the dispersion of Love waves is less than in continental regions. The data for the Atlantic has usually been interpreted as indicating an intermediate type of structure.

The dispersion of the Love waves from a large South Atlantic earthquake has been studied. It was found that the crustal structure in the Pacific, Indian, and Atlantic oceanic regions is essentially the same and differs markedly from that in continental regions. From the dispersion of Love waves no difference could be detected between the structures of the Atlantic and Pacific areas.

The structure calculated for continental areas agrees well with those obtained from the data of local earthquakes and blasts. The data from oceanic regions can be explained equally well by: (1) A structure having no layering but an increase of velocity with depth from a value of about 4.0 km/sec for S near the surface to 5.0 km/sec at a depth of about 500 km; or (2) a 20- or 25-km thick layer of velocity 4.0 km/sec overlying a medium of velocity 4.5 km/sec.

N. H. HECK--I regret the absence of Dr. Slichter, who is now working in the field on the very problem discussed. The subject of Father Macelwane's paper need not be discussed here since through a slight revision of my invited paper on "Seismic contributions to knowledge of the Earth's crust," as presented before the Section of Seismology, it covers the issues raised. In the same paper a statement appears in confirmation of the conclusions in Mr. Wilson's discussion.

F. BIRCH--At best, seismic evidence is capable of giving two kinds of information: (1) Structure, that is to say, the location of regions where there are abrupt changes of velocity; (2) the velocities themselves at different depths. For many, if not most, of the problems of geology and geophysics, it is desirable to know what materials are present at the various levels, characterized seismologically by certain velocities. This kind of identification requires measurements of another sort--laboratory measurements of elasticity, under the appropriate conditions, of relevant geological materials.

There seems to be no purely seismological method by which the necessary information can be obtained. Field-prospecting over well-known material means working at shallow depths; we know, however, that the velocities found for granite by artificial blasts in granite quarries are much lower than those propagated in the "granitic layer" from near earthquakes. Laboratory work shows that the velocities in granite increase markedly with the pressures to be expected in such a granitic layer. Similar effects are found for most rocks. The refined data of seismology can be used to the greatest advantage only in connection with the complementary work, mostly at high pressures, in the laboratory.

J. B. MACELWANE--Basically I am in complete agreement with all of the speakers. However, I would like to emphasize this. Any information that we can get, either by methods so far devised or by new methods, should be welcomed. Any quantitative measurements that can be brought into

the picture will help to fill up the wide gaps that admittedly exist in our knowledge of the Earth's crust. Even details are complementary to those from other sources, and it is the province of the geophysicist to coordinate and to synthesize the data from the various fields so as to paint a picture as complete as possible on the basis of the data available; but I think we would be deceiving ourselves if we were to take the present picture, which is necessarily so very sketchy and incomplete, and make it the basis of deductions which extrapolate far beyond the data on which the picture was drawn.

A. C. LANE--I regret that I have not heard anything regarding the seismic work which seems to indicate keels as, for example, the coastal range in California is said to have. All the speakers seem to speak as if there were one general level for the continents and another for the oceans. There has been some indication of thickening of the crust in some places.

R. M. FIELD--Captain Heck reviewed that situation before the Section of Seismology yesterday.

N. H. HECK--I have the feeling that if we adopt a picture we should not assume that it extended over a very great area. There must be very great differences in the oceans and over the continents.

(2) Thermal measurements and their bearing on crustal problems

A. C. LANE--This very excellent and interesting paper brings up the importance of the general question of heat-flow in a wide range of problems before us. In our mountain-building question we certainly do have some kind of folding, and if we are not going to have sliding continents then we must consider the question of some sort of contraction and this means a loss of energy from the interior represented by heat-flow, but, of course, that is not the only way in which energy comes from the interior. It comes in our geysers, volcanoes, and lava-flows. All have to be counted when considering loss of energy which Rudski and Lord Kelvin discussed in discussing the age of the Earth. This is a very important line that Mr. Benfield is working on. Koenigsberger had a little note not long ago in Mining and Metallurgy [1910, p. 210] calling attention to the fact that generally speaking our lower gradients go with our higher conductivities. That is in a general way true. Of course, there are certain other factors and conductivity implies a certain static condition in our gradients. Benfield has mentioned ice-ages, and that is going to introduce diffusivity. Van Orstrand has pointed out that rapid erosion would produce a factor that will make a difference in the question of computing our heat-flow directly from multiplying the conductivity by the gradient. In a discussion with Professor Fisher up in the Copper Country of Michigan, he has very serious doubts about the actual conductivity as found in the laboratory because of the influence of the moisture. We heard something about moisture in another Section. The moisture in the laboratory has a great deal to do with this conductivity. So far as the sediments are concerned and calcium chloride, it would be desirable to give some idea of the conductivity and diffusivity as they are in the mines, and I think it can be done.

There are, therefore, other factors to be considered. If we have a different thickness of the crust and if at the bottom of that crust there is some sort of a chemical reaction going on, say, crystallization, which gives a sort of fixed temperature, then the thicker the crust the lower the gradient, other things being equal. It has been fairly recently considered by Cleland and also at a place where there has been a lot of heat in times past (in the Keweenaw Bay Region, etc.) and very little in later times, and may not very great stability be due to some extra thickness of the crust which would reflect itself in a lower gradient there. He is working on a very interesting line concerning which there is a great deal to be done. We need some more accurate measurements such as Van Orstrand has been making for years, and must keep in mind the fact that we do have possibilities which should be brought out not merely in the conductivity but also in the diffusivity. We must connect work in the field with the laboratory.

T. S. LOVERING--Dr. Lane has already discussed most of the things that I intended to take up, but something I would like to say more about is in connection with thermal constants. Dr. Lane mentioned the need of diffusivity-determinations. Dr. Benfield spoke of the fact that we use geothermal gradients that are determined in Australia to get the amount of heat-flow in the middle of North America. A study of any handbook of constants shows that conductivity of rocks in Japan may have to be combined with specific heats of German rocks and densities of African rocks to approximate diffusivities of specimens obtained in America! But diffusivity must be known, except in steady-state problems, if you are interested in changes of temperature as well as the outflow of heat. Conductivity is the hardest measurement to make precisely. After you have that, the determination of density and specific heat is so easy to do that there seems little excuse for not determining them and thus making the thermal data complete for each specimen.

In the few places where conductivity has been correlated with thermal gradient to give us a measure of the heat-flow, a considerable difference is evident. Perhaps the amount of heat flowing out in the middle of the North American Continent is much less than at the edges of the Continent. Of course, we can hardly make such a generalization on the basis of three heat-flow determinations. If we had a few hundred, we might evaluate better some of the rather speculative theories of orogony recently published. At least it would be a long step in the right direction to get this quantitative data.

Heat can move in many ways and we know so little about any of them! There is the bodily transfer of heat in magmas, gases, and fluids, the movement by conduction, and the possibility that the heat can cause and also can be moved by convection-currents in semi-plastic masses. Careful laboratory- and field-investigations will ultimately give us a better understanding of the heat-flow in the Earth, and nearly all geologic processes are ultimately traceable to just this.

I wish to say a word or so with regard to the heat-source found in radioactivity. The measurements of radioactivity that have been made are quite inadequate when considered as a sampling job. We take a few small specimens of sediment and then estimate the radioactive content for thousands of feet of section over hundreds of thousands of square miles. At the present time there is a new technique being used among the petroleum geologists--the radioactive logging of the sediments cut by a well. A continuous profile of radioactivity is obtained for the entire depth of a well, and it is easily possible to transfer the log into quantitative units of radioactivity. Please compare in your mind the relative sample value of a 6,000-foot well as against samples of a few grams of rock; I need make no comment. So far, nothing has been done in an effort to get the actual radioactive contribution to the Earth's heat by correlating such logs as are available or logging wells in crystalline rocks. This would seem a possibility worth the consideration of scientists interested in heat-flow in the Earth's crust. If you can obtain records of all deep wells by such methods as the radioactive-well logging, and get in addition the thermal gradient, and the conductivity and diffusivity of the rocks penetrated by the well, I think we would begin to get the precise data we need in working on the general problem of heat-flow in the Earth's crust.

L. H. ADAMS--At this time I wish merely to emphasize the great need for adequate information on thermal quantities under conditions prevailing at various depths within the Earth. In almost every problem of geophysics we encounter the need for a knowledge of temperatures below the Earth's surface and for related information concerning heats of melting and specific heats. The tendency in geologic problems is to pursue them farther and farther into the Earth. We may note, for example, the great attention given in the last few years to the cause of deep-focus earthquakes originating at depths as great as 700 km. If we wish to know the temperature at a given depth, we need quantitative information on five factors before we can construct a curve that will give a series of such temperatures at various depths. These factors are: The age of the Earth; the conductivity or diffusivity of rocks; the temperature-gradient at the surface; the radium-content of surface-rocks; and the effect of pressure on melting point. The information in all of these categories has been quite inadequate and confusing. In combining two of the essential elements--conductivity and temperature-gradient--Dr. Benfield has made a great step forward utilizing heat-flow rather than the individual factors, and thus bringing order out of chaos in this part of the subject. Two other factors--the age of the Earth and the concentration of radioactive materials in the surface of the Earth--may be combined as an expression of the total heat-production, so that the five fundamental factors are reduced to three, that is, heat-flow, heat-production, and the effect of pressure on raising the melting point. The latter is important because, if we believe (as many do) that the beginning of true thermal conduction was coincident with the solidification of the Earth, the pressure-melting point curve marks the temperature at various depths at the time that geology began. Heat-flow, as well as temperature-gradient and thermal conductivity, have been put on so sound a basis by Dr. Benfield's studies that if, as seems likely, radium-content can be put in an equally satisfactory state, it will then be up to the laboratory experimenter to make reasonably complete measurements on the relation between pressure and melting point, after which we can confidently expect to have a better notion of the temperature at considerable depths within the Earth and a starting point for the solution of many basic problems.

F. BIRCH--Direct measurements of temperature in the Earth are at present confined to the outside two or three km. I would like to suggest an indirect method which has the possibility of extending our knowledge of the temperature to considerably greater depths. This method depends upon the use of seismological data in conjunction with laboratory measurements of the effect of temperature upon the wave-velocities at high pressure. At present the variation of velocity within the various crustal layers is not accurately known, but we may assume that the

velocity does not decrease with depth sufficiently fast to produce downward refraction. If we write the condition, relating the temperature-coefficient and pressure-coefficients of velocity, the geothermal gradient, and the pressure-gradient, that no downward refraction occurs, we may derive a maximum value of the thermal gradient for any kind of rock for which the coefficients are known. The relation is

$$(\Delta T/\Delta z)_{max} = [-V/R - (\Delta V/\Delta P)_T (\Delta P/\Delta z)] \div (\Delta V/\Delta T)_P$$

where z is the depth, R is the Earth's radius, T is the temperature, and P is the pressure. For the ultrabasic rocks at about 30 km, our present information yields $(\Delta T/\Delta z)_{max} = 8°/km$. The estimate is likely to be too high rather than too low. Looking at Dr. Benfield's table, we find that such a result enables us to rule out the first two columns; it agrees fairly well with the figure, 6°5/km. With increasingly precise data, and greater experimental ranges of pressure and temperature, this method may afford fairly reliable upper limits for temperature-gradients at depths inaccessible to more direct approach.

In connection with Dr. Adams' remarks, I would like to suggest that the reduction of the problem of the Earth's thermal history to the five factors which he mentions has certain difficulties apart from the determination of the effect of pressure on the melting point of definite materials. One difficulty which seems serious to me is to decide what the primitive material was whose melting curve is supposed to determine the initial temperature-distribution. Methods which are independent of any special theory of the Earth's cooling and solidification seem preferable for determining the present temperatures.

A. E. BENFIELD--In reply to Dr. Lane, we are fully aware of the possibility of trouble with the moisture-content and went to some pains to determine what effect a difference of moisture-content would make on the conductivities. We tried heating the rocks in order to drive out moisture and soaking rocks to increase their moisture. By taking the proper precautions no serious error is introduced on this account. In reply to Dr. Lovering, I should like to say that I fully endorse his suggestion about getting more radioactive information, particularly from as deep as we can. As to the diffusivity, this is connected with non-steady-state temperature-conditions. If the wells at my disposal had been deep enough to date the ice-age with any accuracy I certainly would have measured the diffusivities or the specific heats, but the holes were not deep enough to get more than rough estimates of this date, and there did not seem to be much point in making the additional measurements. Finally, in reply to Dr. Birch, I should like to say that I am glad that he believes that 8°C/km is the gradient at depth, because that is what I should like to think myself, but I think that it would make certain people rather angry. This low temperature-gradient makes possible a reasonable thickness for the granitic layer, but Dr. Birch's idea of temperature-gradients would give pretty low temperatures quite a long way down. A gradient of 6.25°C/km gave us a temperature of the order of 900°C only after going down 90 km.

H. ARCTOWSKI--Extensive temperature-measurements have been made in the oil-wells of Poland especially in Boryslaw [see Geog. J., v. 66, p. 422, 1925]. A small temperature-gradient is characteristic for the Carpathian Mountain Region.

Comparing the data obtained at a depth of 2,000 meters, with those of the coal-fields of Upper Silesia of the same depth, a difference of about 30° C is noticeable, whereas near the surface the temperatures are similar.

Why is this so? Simply because the Carpathians are Tertiary earth-crust foldings, extending deep, while the Hercynian Mountains have been abraded and uplifted. In the first case, at a depth of about 2,000 meters we are farther away from the sima than at the same depth in the Carpathians. In a thin cover of sedimentary rocks, temperatures at a depth of 2,000 meters must be higher than in a thick covering.

(3) Deformation of rocks in the laboratory

R. W. GORANSON--My contribution to the subject is in integrating the large mass of data we have and generalizing the results so that we may be able to work even more intelligently in accumulating further data. There is one comment necessary for the elucidation of Dr. Griggs' diagram on the tensile strength of marble. I should not have been able to understand it if he had not given me some further details earlier in the day.

In compressive tests under hydrostatic confining pressure we have a pressure acting on all sides of this cube and superimposed an added compression along one axis. In the tensile tests a

pressure was initially acting on all sides of the cube, but along one axis some of the pressure was removed by adding a tensional pull. In both cases the external forces were all pressures. In the former case the specimen was under internal pressure along one coordinate axis and internal tension along the other two axes. In the latter case the specimen is under internal pressure along two coordinate axes and internal tension along the other axis. Thus the relations deduced for compressive strength also apply, with only slight modification, to the "tensile-test" data.

If we add "physical properties" to the table of variables set down by Dr. Griggs we are then able to compute our internal energy and free-energy relations. We are thus able to formulate a working hypothesis by which we may hope to interpret the various phenomena of deformation in the Earth's crust.

Without such an hypothesis which correlates and interrelates all the independent variables, any interpretations we make cannot be very much better than pure speculations since we are unable to duplicate processes in nature by means of laboratory models.

M. KING HUBBERT--Dr. Griggs' important experiments on rock-deformation are sufficiently clear as to require no further amplification by me. The problem that I wish to dwell upon briefly is that of what can be done with these results after we have them, in so far as our primary problem of the deformation of the solid Earth is concerned.

During the past century our thinking about the Earth and its deformations has undergone a curious evolutionary history. During most of the nineteenth century it was customary to regard the Earth as a cooling molten sphere having a lava-like interior and a superficial solid crust. Under that conception the observed surface-deformation of the Earth was a simple crustal buckling. Also it was upon the basis of this conception that the Pratt and Airy theories of what has since come to be known as "isostasy" were founded. This made the thickness of the supposed crust one of the important terrestrial unknowns to be determined.

In the early part of the present century the data of seismology began to indicate that the Earth had a rigidity of the order of twice that of steel, at least to the 2,900-kilometer discontinuity. This was confirmed independently by the earth-tide experiments of Michelson and Gale, and others as well, giving an overall rigidity of the Earth as a whole of the order of twice that of steel.

While it is to be emphasized that strength and rigidity are different properties of materials, all of these results pointed clearly to an Earth whose properties were remote from any that could be ascribed to a fluid lava. Griggs' laboratory experiments are likewise in conformity with the known properties of the Earth.

At the same time that data were thus becoming available which showed convincingly that the Earth was not the fluid body we had earlier supposed it to be, the geodesists under the leadership of Hayford were discovering that triangulation- and gravity-networks could best be adjusted on the basis of some sort of assumption regarding isostatic equilibrium. Out of the multiplicity of such possible assumptions, considerations of expedience and ease of computation led to the adoption in a slightly modified form of the hypothesis of Pratt. This proved itself so useful as an adjustment device that we tended to forget the circumstances under which it was adopted and began to become convinced that the hypothesis had reality. Instead of a "thickness of the crust" we spoke of a "depth of compensation" meaning practically the same thing. Instead of a molten interior, we found ourselves postulating lava-like substrata. Our geodetic calculations on the basis of these assumptions gave a "depth of compensation" of the order of 60 kilometers.

In all of this we have within the last decade or so been brought up sharply by the seismological discoveries of the prevalence and frequent recurrence of deep-focus earthquakes extending to depths of more than 700 kilometers, and arising almost certainly in response to excessive shear-stresses at those depths.

Those of us who thought of the Earth as a rigid body having properties comparable to cold steel inadvertently transferred our experiences with small steel balls to the Earth as a whole and were consequently embarrassed to find adequate mechanisms to produce the known deformation of the Earth; those who clung to the hypothesis of a fluid-like interior were equally embarrassed by the accumulating data of Earth solidity.

These apparent contradictions are resolved and we again arrive at the conception of a weak but deformable Earth once we recognize that materials having great strength when considered on a small laboratory-scale become weak and pliable under the ordinary stresses arising from the

Earth's gravitational and rotational fields, when the linear dimensions of the bodies become measurable in terms of hundreds of kilometers. In this manner we find outselves dealing with a weak and highly deformable Earth even if composed of materials having both great rigidity and great strength. Then if we endow the materials with a pseudo-viscosity of the type that Griggs has here indicated, in periods of millions of years we may well expect deformation in amounts comparable to that observed geologically, under comparatively small differential stresses.

Having thus returned to the conception of a weak and highly deformable Earth (although now composed of "strong" or at least highly rigid solids) we are confronted with the problem of dealing with the field-mapping of Earth-deformation on a more comprehensive scale than heretofore has been customary. Here we obviously deal not only with a field-problem as the word "field" is used by geologists, but also a field-problem as the word is understood in physics. We have a strain-field, a density-field, a thermal field, a gravitational field, and a stress-field, all coexisting in the same region of space and all simultaneously involved in any deformation that occurs in that space. In addition we have the great unifying principles of the conservation of matter, and of the first and second laws of thermodynamics in accordance with which supposed material transformations must occur. In other words, we deal with a field-problem of the most general kind in the mechanics of deformable bodies. In view of that fact, it seems only appropriate to point out here that great advances in the analysis of phenomena akin to those here considered have already been made by workers in kindred fields, particularly the mechanics of fluids. While it is not here suggested that the Earth constitutes a problem in fluid mechanics, I should like strongly to urge that many, if fact most, of the methods of analysis that have proven useful in fluid mechanics are likewise, with slight modification, appropriate here. Particularly I should like to suggest that the students of Earth-deformation would accelerate their own work if they took time out to become completely familiar with modern methods of analysis as employed in the domains of hydrodynamics and dynamic meteorology and oceanography.

Just one additional point: One of the most fundamental possible approaches to terrestrial phenomena of this kind is that wherein the Earth is regarded as composed of matter whose amount remains sensibly constant, but whose configuration is changing continuously with time, and that for each material transformation there corresponds a transformation of energy. It has long been customary in geologic thinking to observe strictly the principle of the conservation of matter, yet it is an anomalous fact that outside of restricted types of work such as that dealing with heterogenious equilibria in magmas, the word "energy" in its strict scientific sense is an almost unknown term in geologic science. The result is that we have no adequate criterion of whether or not any postulated material transformation which does not violate the principle of the conservation of matter is still a possible transformation, or whether it violates some of the rigid restrictions to which energy must conform. In fact, I think it would not be difficult to show that some of our more cherished geological hypotheses constitute one kind or another of perpetual-motion mechanism.

The foregoing is intentionally a digression from the immediate subject of rock-deformation. The problem of rock-deformation in the laboratory is only a detail--albeit a very important one--of that of the large-scale deformation of the Earth. My thesis is that our most urgent need of the moment is not more facts, but the development of a comprehensive body of analytical relationships which will enable us to assimilate the facts that we have already and at the same time afford a criterion for what the missing data are that still are needed. It is my opinion that a great deal of this material is already in existence and needs only to be acquired and utilized by the students of Earth-deformation. With this in view, I should like to commend the modern treatises of thermodynamics, and of hydrodynamics and dynamic meteorology and oceanography, to students of this problem.

(4) The mountain-building cycle

W. T. THOM, JR.--To keep within time-limits in discussing Professor Bucher's paper, the writer has decided to confine himself to a brief statement of essential facts bearing on this subject--postponing, for the moment, any presentation in extensio of the detailed evidence validating the conclusions stated. Among the many facts from which we may deduce the "Deformational history of the continents" are the following:

(1) The major structural element of each existing continent is a simple or compound "continental shield," mainly composed of relatively light, strong, and cold rock.

(2) These (visible) shields were formed in remote pre-Cambrian time by successive crumplings, fusings, and weldings of a thinner crust, which was thoroughly injected and heated by (largely) granitic intrusive rocks.

(3) Since their formation, and original planation by erosion, these continental shields have suffered only minor internal deformations and warpings, but have oscillated vertically with respect to sea-level--at times being submerged (perhaps deeply) and at other times rising considerably above sea-level. In consequence of these submersions, large parts of the known continental shields are covered by thin, nearly horizontal layers of sedimentary rocks, as, for example, in the Upper Mississippi Valley.

(4) Around the margins of the primitive continents (shields) long trough-like downwarps of the crust have developed, first here, then there, along weaker strips of the crust. Such downbendings have recurred periodically throughout geologic time.

(5) These "geosynclines" or downbuckles of the crust were produced by the crowding toward each other of two (stronger) continental crustal areas. Characteristically, the axes, or lines of maximum depth in these troughs, developed close to the margin of the higher of the two opposing land-masses.

(6) Material eroded from the higher land-masses kept the downbuckling troughs filled nearly to sea-level, and, as crowding proceeded, these thick prisms of layered sedimentary rock were first folded and then thrust-faulted--being ultimately overridden (or underridden) in part by one or both moving continental masses. The Appalachian-Ouachita system, the Urals, the Atlas-Alpine-Carpatnian-Thibetan mountain zone, and the East Indian island-arcs all afford definite examples of the formation and deformation of geosynclinal belts by the crowding together of pairs of continental masses.

(7) There seem to be many indications that before mountain building began in any region, the subcrustal temperatures of that region had risen notably--as manifest by volcanic and other igneous activity.

(8) After an orogenic (mountain-building) episode, there has commonly been a collapse of the crust behind the arcuate mountain zones developed--such collapse being commonly attended by basaltic intrusions and fissure eruptions (for example, Triassic intrusions of the Atlantic Seaboard; basaltic lava-flows and volcanics of the Great Basin Region of the West, etc.).

(9) Due to such post-orogenic subsidence, one of the continental areas which had previously participated in a mountain-making movement may have subsided to an ocean-floor level (as, for example, in the case of Appalachia, of Llanoria, and of parts of Gondwana-land, etc.)--with the consequence that the resultant coast-line of the yet-emergent continent naturally has tended to follow the outer flank of the newly formed mountain range. Therefore, in general, each new mountain range has tended to lie nearer to the subsequent "continental margin" and at greater distance from the center of the old "continental-shield" area (Cf. California Coast Range versus the main Cordilleran system of the Western United States).

(10) To recapitulate, the evidence yielded by sedimentary rocks of the continents, combined with the available geological and geophysical evidence (regarding the forms and areal patterns of the crust's deformational features) now shows that the continental shields have periodically moved either upward or downward en bloc, and have also moved laterally for distances measurable in scores of miles, if not in hundreds of miles.

(11) In consequence of lateral glidings of the crust over subcrust (such as have produced the crustal downbuckles and associated "negative-anomaly strips" of the East Indian and West Indian island-arcs), it seems practically certain that large "crustal ripples" have developed. Rapid (local emergence of the ocean-floor along the crest of such a ripple would be speedily followed by resubmergence (as the ripple passed on toward the downbuckling tetogene),thus affording the conditions needed both for the cutting and preservation of submarine canyons, and for the rise and subsidence of the "land-bridges" which have been postulated by paleontologists and biologists to account for the (otherwise inexplicable) distributions of terrestrial and marine life-forms.

(12) The lateral glidings of the crust have not taken place uniformly or with equal rapidity at all points along a given orogenic zone, due either to local variations in the strength and thickness of a particular downbuckled crustal strip, to regional variations in the mobility, or degree of liquefaction, of the asthenosphere (subcrustal "zone of weakness"), or to protuberances on the bottom of the moving crustal sector.

An "asthenosphere" is either continuously or recurrently developed beneath the continental shields, beneath the downbuckled "geosynclines" (or "orogens" or "tectogenes"), and beneath the ocean-basins. This is the "zone of mobility" which permits of isostatic readjustments.

(13) Available geophysical and geological evidence indicates that vertical and lateral crustal movements are still going on--especially in the circum-Pacific Region; along the Mid-Atlantic Ridge; and in the Mediterranean-Himalayan-East Indian Region. Such movements have been of great magnitude during and since Pleistocene time, and either are occurring, or will recur, along the world's major seismic zones--presumably by sudden, quick shifts, separated by much longer periods of (relatively) quiet stress-accumulation.

(14) The recurrence of identical deformational patterns on both the ocean-floors as well as on the continental platforms; the occurrence of crustal downbuckles (partly expressed by "fore-deeps") as, for example, along the west coast of South America, along the oceanward slopes of the West Indian, East Asian, and East Indian island-arcs, and east of the Tonga islands; and the occurrence of linear volcanic chains (along sub-oceanic faults), as, for example, in the Hawaiian group, all serve to prove that "sub-oceanic crustal shields" also exist--presumably differing from the "continental shields" only in the average density and composition of their component rocks--while having essentially identical strength-characteristics, stress-responses, and (resultant) deformational patterns.

(15) Considering the foregoing evidence, and one of Newton's laws of motion (that action and reaction must be equal and in opposite directions), the writer concludes that the deformational features of the continents are not different either in form or in manner of origin from those characteristic of the Earth's surface as a whole. He believes that these world-wide deformational patterns are due either (a) to a crumpling of thin strips of crust between thicker, stronger shield areas or (b) to a splitting and fracturing of the margins of moving shields, accompanied by (c) a rotational twisting of the crust (around either vertical or horizontal axes). Rotations of this sort would result from an unequal rate of lateral shift of different parts of a moving crust (such as could, alone, have been responsible for the production of the known deformational features of the Earth's surface). Furthermore, the observed patterns prove that the moving crust must have been continuous over the whole globe and must have been underlain by a relatively more mobile subcrustal material. Under this concept, mountain-building can not have been due to "continental drift", but has, instead, resulted from (relative) crustal shift, caused by periodic readjustments between a crust which has (recurrently) become (relatively) too large to fit the volume of the Earth's interior.

(16) To harmonize isostatic and geologic evidence as to the structural composition and deformational history of the Earth's crust, it is necessary to realize that crustal uplifts and depressions have been due to a combination of isostatic influences plus tangential compressive stresses. Neither isostatic readjustment nor tangential thrust alone can have produced the deformational pictures which are before us.

It is, furthermore, necessary to realize that it is only accidentally and locally that the bottom of "the Earth's crust" coincides with the bottom of "the granitic layer, or sial." Usually, the mechanically-effective crust of the shield-areas extends far below the bottom of the granitic layer and into the underlying basaltic layer, if not through it. Presumably both past and present "orogenic zones" have been localized along belts in which subcrustal temperatures have risen to a point where the basaltic layer has lost its structural competence.

A vertical section through a normal "oceanic shield" portion of the Earth's crust should, then, consist of a thick layer of strong basaltic rock--covered by a veneer either of oceanic sediments or of terrigenous material. Within "continental-shield" areas, by contrast, the basaltic foundation-layer would be overlain by a considerable thickness of lighter acidic rocks--perhaps in turn covered by a veneer of stratified sediments. Such "continental-shield" regions would lie above sea-level almost indefinitely (so long as isostatic balance was not seriously disturbed by tectonic forces), being all the while gradually lowered by erosional down-cutting, which would gain slowly on isostatic reelevation. However, where isostatic balance of a region has been strongly disturbed (through recurrent reelevations induced by tangential thrust) it may have happened that much or all of the upper, light, acidic part of the crust has been completely eroded and shifted laterally by river-transportation. And in any area where this has happened the ultimate relief of the tangential stresses (through folding and thrusting movement) would necessarily be followed by isostatic subsidence of that region to sub-oceanic depths. (This, apparently, has happened in the known instances of Appalachia, which lay off the Atlantic Coast of the United States, and of Llanoria, which once occupied the position of the present depression of the Gulf of Mexico.)

In conclusion, it can be stated with confidence that we need to replace our existing plethora of structural theories with an even greater number of new geophysical and geological facts--for only in this way can we attain to a really scientific understanding of the deformational and evolutionary history of our continents.

Similarly, we need to learn much more regarding the composition of the Earth's crust and regarding its general mechanics of deformation. And we need to discover the causes productive of the notable (lateral) differential shifts of parts of the Earth's crust--such as are of interest and importance to geophysicists, geologists, and astronomers, alike.

H. H. HESS--There is a well-established, widely held concept that the following sequence of events takes place during mountain building: (1) A long narrow trough ("geosyncline") fills slowly with sediments commonly of predominantly shallow-water origin, the trough slowly sinking as sediments are poured into it; (2) after a great thickness of sediments has accumulated this downwarp of the crust is considered to be weaker than the normal crust and will tend to localize mountain-building strain; (3) thus when forces producing mountain building arise, the trough filled with sediments becomes strongly deformed, folded, and faulted, and is transformed into a mountain system. This concept may be traced back almost one hundred years to the ideas of James Hall on the Appalachians. The concept should now be critically reexamined for it is fairly apparent from evidence now available that it is almost completely false.

The actual sequence of events, judging from island-arcs, seems to be more nearly as follows: (1) A long period of slow sedimentation takes place in moderately deep water in a broad sea marginal to a continent (not a "geosyncline")--the total thickness of sediment thus developed is not great; (2) sinking of a narrow trough in this sea to great depth is accompanied by submarine eruptions of basaltic magma which results in interbedded volcanics and radiolarian cherts; (3) buckling of the upper crust to form a "tectogene" is accompanied by the intrusion of peridotites--the weak sedimentary mantle may be squeezed up out of the core of the downbuckle to form a ridge along its axis or if insufficient mantle is present a great ocean-deep may be formed along the axis; (4) emergence of the geanticline commonly on one side of the downbuckle--the concave side--accompanied by andesitic volcanism also on the concave side; (5) the basins ("geosynclines") behind the inner geanticline (concave side) or/and outside of the outer geanticline receive a huge thickness of coarse clastic sediments eroded from the rising geanticlines and perhaps also from the up-squeezed core of the downbuckle; (6) later deformations pushing the Earth's crust deeper in the buckle shove these basins filled with clastic sediments up against the further up-squeezed material over the core of the buckle, producing superficial folding of the basin-sediments and alpine-type thrusts in the up-squeezed rocks; andesitic volcanism continues. The post-deformation events will not be considered at this time. The above sequence obviously is highly speculative and no doubt will be modified when more information is available.

In the above sequence the area of folded Appalachians would correspond to the secondary basins formed to the side of the tectogene structure after its development. The wide-spread Cambro-Ordovician, calcareous, and argillaceous rocks in the Appalachian sequence would represent the marginal-sea stage. The first great deformation with buckling of the crust would be the Taconic which is known to have been accompanied by the typical peridotite intrusions. The great thicknesses of Silurian and Devonian coarse clastics result from the post-buckling uplift into mountains of the region of the tectogene. The tectogene was under the present Piedmont belt, which area was the land-mass referred to as "Appalachia." The Appalachian Revolution was caused by further downbuckling of the crust under the Piedmont area and the shoving of the Appalachian geosyncline with its thick series of clastic sediments up against the then high area of the Piedmont, causing superficial folding of the sediments. The speaker would stress the point that the Appalachian Basin was a wide, fairly deep sea with only a moderate amount of sediment until the Taconic Revolution, after which it became a geosyncline, a narrow trough which filled with a great thickness of shallow-water coarse clastic sediments. This is quite contrary to the concept that the geosyncline localized mountain building for actually the geosyncline was a product of the mountain building.

A similar story is told by the Swiss Alps. The Jurassic is represented by a relatively thin sequence of deep-water sediments of a marginal sea. Buckling first takes place about the end of Jurassic with intrusion of peridotites. The second great deformation occurs in the early Tertiary, squeezing material upward and outward from the core of the buckle to form great thrust-sheets, which if deeply eroded would correspond to the Piedmont belt of the Appalachians. To the north great thicknesses of clastic sediments were deposited which in subsequent movements, as in the case of the Appalachian geosyncline, were shoved against the Alps to form the superficial folds of the present Jura Mountains.

The same sequence of events will hold for the East and West Indies, the Urals, the Himalayas, and many other mountain systems. Though it is probably applicable to the Nevadian mountain system of the Jurassic along the Pacific Coast of North America, it does not apply to the Laramide Rocky Mountains which appear to be of quite different structure and history. The latter have no belt of peridotite intrusions, no geosyncline of the Appalachian type, and they appear

to represent mountain-building forces acting on a continental type of crust rather than on the crust of a sea marginal to a continent. Release of stress seems to have been accomplished mainly by steep thrust-faults over a broad area instead of downbuckling of a narrow belt. It may be noted that a very great thickness of sedimentary rocks was present in a basin in the general vicinity of present Utah from Belt times until the Laramide folding. Nevertheless, the Nevadian folding was localized not in this basin but to the west in a marginal sea in the area of present California.

JOHN L. RICH--With reference to the peculiar basins which Dr. Bucher has described: Some years ago, before the Geological Society of America, I gave a paper on the origin of geosynclines whose essential idea was that, on the borders of a rising mass being eroded, isostatic sinking should be expected to take place because of the subcrustal migration of material toward the rising area. It seems to me that sinking over any considerable area of the surface of a sphere having a "crust" must necessarily lead to the formation of basins with relict higher areas between them, rather than to features like long linear mountain ranges. It seems to me, therefore, that regional sinking or contraction due to any cause would tend to produce basins of the type which Dr. Bucher has described.

B. GUTENBERG (Seismological Laboratory, Pasadena, California)--After reading the foregoing discussion, Dr. Gutenberg has made the following comments on the symposium:

(1) Seismology and the first hundred kilometers of the Earth

As Mr. Wilson has pointed out, the results on crustal structure found from the dispersion of surface-waves should be supplemented by other information wherever possible. From the data available it seems that the velocity of surface-waves in the bottom of the Atlantic Ocean is noticeably smaller than in the bottom of the Pacific Ocean only for waves with periods of about 20 seconds or less, so that it is impossible to draw conclusions only from the fact that the velocity is about equal for longer waves. On the other hand, amplitudes of waves reflected under these two regions show large differences. Recent investigations (jointly with Dr. Richter) of shocks originating at various points of the Easter Island Rise and recorded at Huancayo (Peru) have confirmed the previous findings that "continental" reflections seem to be the rule in the area between this Rise and Huancayo. The existence of such outlying areas with "continental" structure in the Pacific and the distance of most stations from the true Pacific Basin have the effect that purely "Pacific" paths are scarcely available in investigating the dispersion of surface-waves in various areas. On the other hand, the so-called "Atlantic" paths contain various types of structures. A comparison of the dispersion-curves along both types of paths, therefore, gives only approximate results.

(2) Thermal measurements and their bearing on crustal problems

Thermal measurements are available only for a limited part of the Earth's crust, mostly in disturbed regions. Data from oceanic areas are practically missing. Such data, even from small non-volcanic islands, may change the assumed "average" thermal gradient near the surface by a large fraction.

(3) Deformation of rocks in the laboratory

There is no doubt that the application of results found in laboratories on a small scale to the large scale in nature must be done very carefully, as has been pointed out by Dr. Hubbert. However, it is not necessary to assume that generally "materials having great strength when considered on a small scale become weak and pliable ....., when the linear dimensions of the bodies become measurable in terms of hundreds of kilometers." Even the highest and most extended mountain systems seem to persist without noticeable change and indicate strength of the magnitude found in experiments with samples, whereas stresses arising from the melting of the ice after the ice-age and amounting only to a few per cent of the stresses produced by the weight of the mountains are large enough to produce changes noticeable within a few years. If plastic flow with this speed had occurred under the Alps, their height would have been reduced by almost one-quarter since the time of Caesar. It seems to be possible to explain all observations in agreement with experimental findings by assuming that the crystalline lithosphere (down to a depth of about 70 km) has strength of the order of 10^9 dynes per cm^2, and that the (probably vitreous) asthenosphere below it has no perceptible strength but a viscosity so great that it takes plastic flow about 10,000 years to decrease a given stress to about one-half of its original value. A small but definite discontinuity between the two layers is indicated by seismic data. If a process (as melting of extended ice-caps, or tectonic changes) produces stresses below this dis-

continuity (occurrence of isostatic gravity-anomalies), plastic flow in the asthenosphere will result. Where stresses are limited to the lithosphere ("isostatic compensation" of mountains, oceans) nothing will happen as long as the resultant stress nowhere exceeds the strength of the material. Wherever this stress increases beyond the breaking strength, an earthquake will be the result, regardless of whether this happens in the lithosphere or in the asthenosphere.

This picture is only a first approximation. This is mainly due to the fact that the processes are neither purely elastic nor purely viscous. Elastic afterworking, pseudoviscosity, and other phenomena not yet well understood complicate the processes. But these complications are not restricted to nature but have been found in smale-scale experiments as well.

AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF GEODESY

REPORTS AND PAPERS

Washington, D.C.

April 25, 1940

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THE WASHINGTON MEETING OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS, SEPTEMBER 1939

Walter D. Lambert

The invitation to the International Union to meet in Washington in 1939 was given at the Edinburgh meeting of the Union in 1936. The invitation had the approval of the National Research Council, which is this country's adhering organization for all international unions, and was extended by the head of the American delegation at Edinburgh.

It was hoped that Congress would appropriate money toward the expenses of the meeting. This Congress did about a year ago and the President of the United States then invited not only the adhering countries to send delegates but other countries also. It was hoped that Latin-American countries, which as a whole have taken no great part in the affairs of the Union, would see fit to send delegates.

Even in 1936, when the invitation to meet in Washington was given, trouble was brewing on the international scene. As time went on, the situation became increasingly ominous. From abroad informal suggestions began to come in that the meeting be postponed. General American opinion was that nothing would be gained by postponement, since matters seemed likely to get worse rather than better with the passage of time and since a postponed meeting would probably not be held at all. When the President and Secretary of the Union asked whether postponement would be considered, the matter was taken up with the State Department. The reply was against postponement. It was further stated that if the meeting were held, but under unfavorable conditions, scientific matters only would be considered, to the exclusion of financial and administrative matters.

As you know, matters went from bad to worse. The situation was very tense when the first foreign delegates began to arrive towards the end of August. Various informal conferences were held in which the Chairman, the Secretary, and other members of the American Committee of Organization met with the leading foreign delegates.

Small wonder then that much uncertainty prevailed and that by misunderstanding newspaper reports were printed to the effect that the meeting had been abandoned. Confusion was inevitable, so to meet this situation the following communication, signed by President la Cour and General Secretary Winterbotham, was sent from Washington, D. C., August 30, 1939, to all leading delegates who could be reached and denials of the reported abandonment of the meeting were published in the press:

"At the opening of the Seventh General Assembly of the Union the Bureau feels it advisable to say a word about the present situation.

"The unfortunate political crisis of the moment has greatly diminished the attendance from European and other countries. Moreover, it is impossible, at the moment, to effect free transfers of the funds of the Union or of the Associations from one country to another.

"In view of these facts, we consider it impossible at this moment to come to any constitutional decision on matters of administrative or financial change. There are, however, two good reasons for making the most of the scientific possibilities of the Assembly: Firstly, many of our colleagues, present or absent, have prepared valuable papers for discussion, and, secondly, our hosts have spared no trouble in ensuring an efficient and thought-provoking program. After consulting the American Organizing Committee, and as many of our colleagues as possible, we have therefore cabled to all adhering organizations as follows:

"Washington General Assembly International Geodetic and Geophysical Union proceeding Stop Activities confined to scientific matters only Stop Winterbotham la Cour

"If the assembled delegates agree, the Conference will be governed along these lines; no administrative or financial change will be made, and no elections will be held. All scientific papers will be presented as scheduled, and whenever any author is absent, someone will read the paper for him."

So the meeting was held. It was pure luck that events so timed themselves that the dates set long in advance were as favorable as could have been picked, even with foreknowledge of the future. If the meeting had been held a little sooner, delegates from all the countries shortly to be at war would have been there and the atmosphere would have been decidedly unpleasant. A little later and the meeting could not have been held at all.

I shall not attempt to rehearse all the details even for the Association of Geodesy, much less for other Associations. What happened in the Association of Geodesy most of you already know.

It was a great relief in the meeting of the Union to be rid of financial and administrative matters. Only those who have attended other meetings of the Union know what a wearisome amount of time these things used to take, to the exclusion of more interesting and important matters.

The exigencies of the situation caused an entire overhauling in the procedure of the Association of Geodesy. Previously much of the work had been done in committee. Some of the committee meetings were then well attended, not only by regular members but by others; the discussions were often animated and interesting. The committee reports, when made, were adopted in the final plenary session, purely as a matter of form.

Last September so many chairmen and secretaries of committees were absent that this procedure was impracticable. Instead of two or three plenary sessions for routine or administrative matters held towards the beginning and the end of the meeting, every session was a plenary session. Each session was devoted to a single subject under the leadership of some authority on that subject.

In some ways this was more satisfactory than the previous procedure and the opinion was expressed that it might be desirable to continue it at the next international meeting, if and when held. How far this will be practicable remains to be seen. The program of the Association of Geodesy is usually very heavy and to some extent must probably always be dealt with in committee under normal conditions. The committee method has some advantages and some disadvantages, among which latter is the fact that it sometimes requires a delegate to be in two places at once for committee sessions. If the delegate is an officer or a leading member of both committees, the disadvantage is serious. Perhaps some compromise form of procedure will be worked out--more plenary sessions than in the past and less committee work, although still a substantial amount of it.

The Executive Committee of the Association of Geodesy held a special emergency session on September 1 before the return to France of General Perrier, Secretary of the Association. At that meeting the Secretary's report was considered and recommendations were made for the Secretary's guidance in regard to financial matters, all recommendations in regard to expenditures being inevitably subject to the qualification that the money be on hand to meet them. It was impossible to avoid some consideration of finance. The form of procedure during meetings actually adopted was outlined.

A meeting of the Permanent Commission, more or less informal because of the absence of so many members, was held on Labor Day, September 4. This ratified the decisions of the Executive Committee. The Permanent Commission is peculiar to the Association of Geodesy and is a reminiscence of the old International Geodetic Association, the last meeting of which was held at Hamburg in 1914. This Commission is composed of a designated representative from each country and, since on administrative and financial matters the vote is by countries, the decision of the Permanent Commission really settles such matters.

As you know, the Association adopted resolutions on various scientific proposals, especially those connected with the subjects discussed in the plenary sessions and reported on in Bulletin géodésique No. 62, of which a provisional edition was available. Many of the resolutions in this No. 62, which had been proposed in the reports of various committees, were not considered at all.

The decision not to take up administrative matters, a phrase that includes elections, had the effect of automatically prolonging the terms of office of outgoing officers of the Union and of its Associations.

The Executive Committee of the Association of Geodesy now consists of the officers of the Association and four members-at-large, as follows:

Officers

President, F. A. Vening Meinesz (hold-over), Netherlands
Vice-President, E. Soler (died January 24, 1940), Italy
Vice-President, W. D. Lambert (hold-over), United States of America
Secretary, Georges Perrier, France

Members-at-large

K. S. Klingenberg, Norway
J. Maury, Belgium
N. M. MacLeod (hold-over), Great Britain
K. Weigel (hold-over), Poland

The naming of members of scientific committees and of reporters for special subjects is a

scientific rather than an administrative matter. Membership in scientific committees in the Association of Geodesy has always been on a rather informal basis. At Washington the basis was made still less formal. Any delegate so desiring may be made a member of a committee by placing his desire on record with the Secretary.

The reporters for special scientific subjects were continued but the Executive Committee was authorized to name successors to reporters unable or unwilling to serve. The late Vice-President Soler was also Reporter for Gravity on Land. It is understood that Professor Boaga, a former student of Soler, aided him materially in compiling recent reports on gravity. Professor Boaga will probably be named Reporter to succeed Professor Soler. The vacancy in the Vice-Presidency will remain unfilled until the next meeting of the Association.

What now of the present and future? As to the future I am neither a prophet nor the son of a prophet. The next newspaper that you read, or the next radio bulletin that you hear, may bring word of events that will vitally affect the fate of the International Union.

Even about the present or the recent past I can say little because I know little. The President of the Union, Dr. la Cour, is a Dane. Even before the invasion of Denmark we heard little of his doings. The Secretary of the Union, Brigadier Winterbotham, has been in military service but it is understood that he has now returned to civil life and has time enough for his duties as Secretary. Of the President of the Association of Geodesy, Dr. Vening Meinesz, we hear that he keeps in close touch with the Secretary, General Perrier. General Perrier is retired and is above the age below which he would be still liable to be called for service in emergencies. He is carrying on the work of the Secretary's Office with a reduced personnel.

I do not know how well the dues of the countries adhering to the Union are coming in. War-time restrictions on international exchange have made it desirable to open accounts for the Union in more than one country. Some distribution of available funds to the various associations has been made by the General Secretary of the Union.

General Perrier published an extensive report on Bases and Triangulation in time for the Washington meeting. One volume of national reports for the Washington meeting is ready and material for another volume is being assembled. At the meeting a provisional edition of Bulletin géodésique No. 61, the first number of 1939, was available. A final corrected edition has now been issued. A provisional edition of No. 62 was also available; a final edition with no less than nine additional articles on leveling is ready for publication. No. 63 is in press; this contains Vening Meinesz's tables for regional isostasy. Enough material is in hand for No. 64. No. 65, the first number of 1940, will contain the proceedings of the Association of Geodesy at Washington. The general reports, that is, reports on triangulation, gravity, projections, and the like, are paged independently but bound in one volume. When a report is ready, printing can begin. Such general reports as are ready are now being printed.

Postscript--In order to obtain material for this paper a request for information was sent to General Perrier, Secretary of the International Association of Geodesy. His reply was received just too late to be used in the paper as actually delivered. The following excerpts are translated from General Perrier's reply:

"By prudent management the Association of Geodesy has fortunately acquired reserves that will permit it to go on for some little time, even if it should not receive further payments from the General Secretary of the Union, but this situation cannot last indefinitely.

"In the quarters occupied by the Association a vault has been fitted up with pigeonholes to hold the most valuable documents in case of a bombardment of Paris, but this eventuality has not yet happened.

"Volume II of 'International bibliography of geodesy', which appeared in the middle of 1939, has not been distributed gratis except to a few leading persons in the Association. Other persons and organizations that might be interested in it have been informed that it must be paid for. It is remarkable that a very small number of subscriptions has resulted. For example, Mr. Lambert in Washington could obtain only one subscription.

"Under these conditions it is probable that it may be necessary to go back to a system of free distribution, if the funds of the Association permit it, or else to interrupt a publication, the sets of which promise to be very useful. Volume III (1935, 1936, 1937) is in press, and Volume IV (1938, 1939, 1940) is in preparation.

"The Isostatic Institute at Helsinki set up by the Association of Geodesy has continued to function in a really astonishing way during the Russo-Finnish war, although a part of the Institute had been moved 150 km north of Helsinki. Another memoir is soon to be added to the six memoirs already published by the Institute.

"In short, for the moment, the Association of Geodesy can continue to live and to work. It is very desirable that it should be able to continue its activity without interruption during the war (like the other Associations of the Union and like the other Unions) in order to avoid any stoppage of international scientific work, which would be very difficult to reorganize when the war ends, but it is essential that the financial question be settled as soon as possible in such a way as will allow it to continue its existence."

U. S. Coast and Geodetic Survey,
Washington, D. C.

SOME PROBLEMS CONCERNING BASIC GRAVITY-DATA

C. L. Garner

It is the purpose of this paper to discuss briefly some of the problems concerning the work of the Coast and Geodetic Survey in making gravity-observations at basic stations as the means of furnishing fundamental data to all interested parties.

As a preface to this discussion, it may be said that the Coast and Geodetic Survey has carried on a very moderate program of gravity-observations since 1873. All of the observations have been made by use of various forms of pendulums. Since about 1890 the work has been done with either bronze or invar Mendenhall half-second pendulums swung in partial vacuum.

Over the years there have been numerous improvements in different parts of the apparatus or in the method of procedure. The most important of these was the development by the late Lieut. E. J. Brown of the apparatus bearing his name which employs a photoelectric tube in making the chronographic record of the pendulum-swings. There were also some slight alterations in the Mendenhall pendulum without changing its basic characteristics. The more accurate recording device made it possible to shorten the observations and thus speed up the work to one gravity-station in six hours of observations or a total of one day's time at a station.

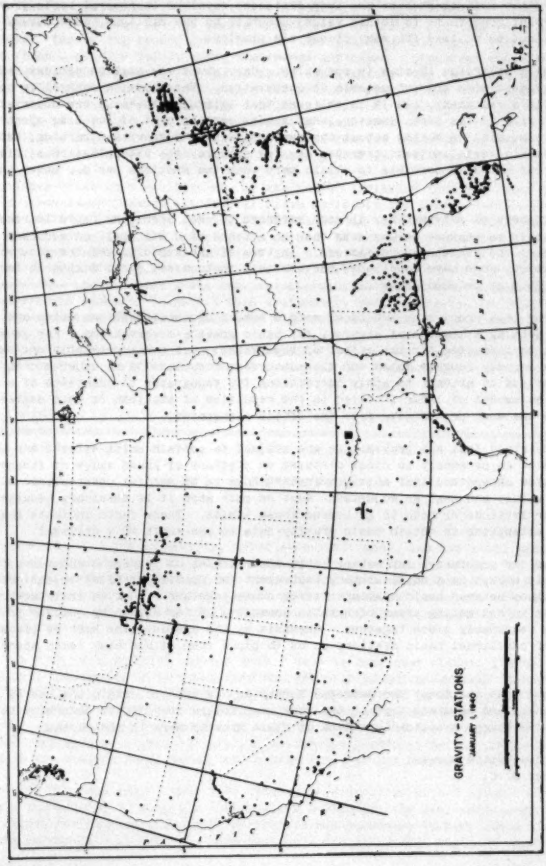
Other improvements concerned chiefly the means of obtaining increased accuracy in time-determinations which have very critical effect on the accuracy of pendulum gravity-observations. Accurate time-determinations, always essential for our gravity-observations, have been obtained by different methods developed from time to time with the progress of the work. In the early work, time-determinations were obtained by astronomical observations at the gravity-stations. This was a laborious process and required considerable time, particularly where weather-conditions were unfavorable for long periods. Later, time-determinations were obtained by comparison of chronometers with Naval Observatory time as transmitted over the Western Union telegraph-wires each day. This had its inherent faults also, as it was frequently not possible to locate the gravity-station near the telegraph-office and it was necessary to use a back-chronometer in making comparisons of time with the standard chronometers at the gravity-station, often as much as a mile away from the telegraph-office.

With the advent of radio and the broadcasting of time-signals from Arlington, steps were soon taken to develop a device for recording the radio time-signals mechanically on a chronograph. This device was designed at the request of this Bureau and was completed in 1921 by Dr. E. A. Eckhardt and Dr. J. C. Karcher, then of the National Bureau of Standards. With this it was possible to obtain time directly from the Naval Observatory, a great step forward in speed and economy as well as accuracy. On some recent gravity-observations, both at sea and on land, time-control has been obtained by use of the crystal-chronometer developed by the Bell Telephone Laboratories. Through the cooperation of that organization and the American Geophysical Union, this chronometer was loaned to the Coast and Geodetic Survey for certain special projects. Time as furnished by the crystal-chronometer is perfect for all practical purposes, and its use has made it possible for the Coast and Geodetic Survey to make a number of very important advances in the development of its pendulum-equipment to obtain a higher degree of accuracy than previously possible. This type of chronometer has not been used in recent field-observations, but it is hoped that one may be obtained in the near future and applied to all future gravity-observations. Where this instrument is used for time-control, the past uncertainty with regard to the very critical feature of time-corrections is eliminated.

The first gravity-observations were solely for the purpose of deriving a more perfect figure of the Earth. They were later used in isostatic studies. Their use for exploratory work has been steadily increasing for some 20 years and at the present time far exceeds their value for purely scientific purposes. In order to meet the demands for basic gravity-information in those

regions of the United States considered most important economically, it has been suggested that there should be a network of basic gravity-stations distributed over the United States not more than 25 miles apart. Some have insisted that the spacing of the stations should be closer. However, gravity-stations spaced generally 25 miles apart in most of the country would require about 5,000 stations altogether, and this will require many years of work at the present rate of progress. During the last two decades, great advances have been made in the development of special instruments, generally known as gravimeters, for the determination of gravity as one of the correlate means of investigating local subsurface structure likely to contain oil or minerals. For such observations, it is desirable that the instruments be checked frequently at basic stations. The Coast and Geodetic Survey data for stations reasonably near the field of operations have been in constant demand.

Up to the present the Bureau has established some 1,050 stations, most of which are dis-



tributed rather generally over the entire country. It is only during recent years that stations have been selected to furnish basic data for the exploration-geophysicists and geologists as well as for strictly scientific purposes. The density of the stations in most sections of the country is far from that desired to provide reasonably accessible gravity-stations for use in regions considered important from the commercial and economic standpoints. In making intensive gravity-surveys, geophysicists require basic values as near to the center of their operations as practicable in order that their instruments may be checked from time to time as a means of obtaining full correlation of all the work in any general region.

The Coast and Geodetic Survey is by law authorized to obtain and distribute control-data, and, therefore, has a specific interest in measuring its basic gravity-stations as reliably as possible at moderate cost. So far as practicable, the data should be such as to meet the requirements of all users. Gravity-values for all stations in the United States are furnished in even milligals--in fact, it is not practical with the pendulum-type of apparatus, or any other, to obtain much greater refinement over the long distances involved in general basic gravity-surveys. Our most important concern is to obtain values accurate to one milligal, an accuracy that unfortunately cannot be claimed for many of our old stations.

The pendulum-apparatus is slow in operation. Only about one station per day can be obtained with this instrument with present methods of observation. Thermostatic control is now being applied to our field-equipment, and it is believed that this will speed up the observations considerably. In view of the fact, however, that a considerable part of the time spent at a gravity-station is not employed in making actual observations with the gravity-apparatus, but in obtaining the supplemental data incident thereto, as, for example, the determination of elevations and latitude, it does not seem possible to obtain more than two stations per day under any conditions.

The development of gravimeters, already referred to, has been very rapid in recent years, and it is possible to measure values with them to a tenth of a milligal, an accuracy never attempted in any of the pendulum-observations. In view of the rapidity and the accuracy claimed for the gravimeter, some have questioned whether this instrument is not adaptable for obtaining basic gravity-data at reduced costs.

In studying this problem we are faced with a number of considerations which are of prime importance in setting standards of accuracy for basic gravity-observations. For general use such data must be corrected for the effect of topography. Our country is only one-half mapped. The topography is only roughly known and the subsurface structure is so uncertain as to make it absolutely hopeless to attempt to apply corrections for topography to one-tenth of a milligal. Furthermore, the amount of labor involved in the reduction of stations to this degree of accuracy would make the work prohibitive from the office standpoint.

It is understood that all gravimeters are subject to certain drift-effects and that to correct for these it is necessary to close circuits on stations of known value at frequent intervals. It is also understood that most gravimeters have to be set for observations within a certain range of values and that an adjustment must be made when it is necessary because of changes in elevation or latitude or both to go beyond those limits. These facts indicate the impracticability of attempting to obtain basic gravity-data to one-tenth of a milligal.

The use of the gravimeter for making basic observations of present standards appears equally impracticable except as a supplementary instrument for special detailed investigations or to interpolate values between basic stations fairly close together. Such an instrument would be of great value for investigating areas of erratic anomalies or for obtaining quicker profiles between basic stations reasonably close together. Emphasis at the present time must be placed on the distribution of additional basic stations so as to place them within easy reach where most needed.

It is hoped that the Coast and Geodetic Survey may be able to obtain the use of a gravimeter of the most modern and accurate type in the very near future in order to determine to what extent it may be applied to the practical problems of basic gravity-work in the Bureau.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GEOLOGIC INTERPRETATION OF GRAVITY-ANOMALIES IN SOUTHEASTERN OKLAHOMA

Thomas A. Hendricks
(Published with the approval of the Director, U. S. Geological Survey)

(Abstract)

Determinations of the value of gravity by pendulum and computations of gravity-anomalies were made by the United States Coast and Geodetic Survey for 14 new stations (Nos. 977 to 990) in Atoka and Bryan counties, Oklahoma, in 1938-39. The stations were located at or near township-corners and were spaced at intervals of about six miles in an approximately rectangular grid. The stations lie on or adjacent to the north border of the Gulf Coastal Plain. North of the Coastal Plain are two prominent fault-systems. One is the belt of overthrust-faults at the northwest side of the Ouachita Mountains. It trends south-southwest and separates a thick sequence of light clastic sediments to the east from a sequence of limestone and dolomite and some granite to the west. The second belt of faults trends east-southeast and lies west of the belt of thrust-faulting. Two of the faults in this belt, the Tishomingo and Ravia faults, dip at high angles and bound a granite uplift along Tishomingo anticline. Limestone and dolomite with some clastic sediments are present north and south of the granite. The two fault-systems converge toward the south and pass beneath the thin sedimentary cover (1,300 feet, maximum) of the Coastal Plain. The gravity-stations surround the junction of the prolongations of the surface-traces of the two fault-systems. The gravity-anomalies range from +56 milligals on the granite uplift to -18 milligals above the edge of the sequence of clastic rocks of the Ouachita Mountains with an average difference between stations six miles apart of 12.5 milligals.

Isoanomaly lines drawn on a geologic map of the region indicated that the broad granite uplift continued southeastward beneath the Coastal Plain sediments for about 15 miles beyond the junction with the prolongation of the frontal thrust-faults of the Ouachita Mountains system. Consequently a deep reentrant in the tract of the Choctow Fault, which forms the front of the Ouachita Mountains, was inferred. This inference has since been verified both by other geophysical work and by data from several old oil-test wells supplied by various petroleum geologists. These data show that in some areas gravity-observations may be used successfully to delineate major structural elements beneath a thin sedimentary cover unrelated to those features. They also show that stations six miles apart have significant gravity-differences.

A complete paper discussing these gravity-determinations and the conclusions drawn from them is to be submitted for publication in the Bulletin of the American Association of Petroleum Geologists.

U. S. Geological Survey,
Washington, D. C.

GRAVITY IN SEDIMENTARY BASINS

D. C. Skeels

Determinations of the force of gravity, which were first made, and are still made, for geodetic purposes, are also important data for the science of structural geology. In recognition of this fact, oil-companies have spent and are spending millions of dollars on their own gravity-surveys. These surveys conducted with instruments which surpass the pendulum, both in accuracy and in speed of operation, are usually directed toward finding minor geologic structures, such as might contain oil or gas.

But it is not with such detailed surveys that I have to deal now; rather, I shall discuss some of the geologic inferences to be drawn from the geodetic pendulum-surveys. Except for some of the figures in Table 1, none of my data is new; they may be found in the various published lists of pendulum-stations. Where my figures as for the Bouguer anomalies do not agree with the published figures, it is because I have recalculated the latter in order to have all anomalies on the same base. The Bouguer anomalies were all calculated according to the International Formula of 1930 on the Potsdam base, using the density 2.67 for the Bouguer reduction.

For many of the stations that I have used, isostatic reductions do not exist. As Bouguer anomalies contain the effects of both the compensative masses and the near-surface geologic masses (as well as deeper non-isostatic geologic masses) it was necessary in many cases to make some kind of isostatic correction, in order to show what part of the anomaly might be ascribed to

isostatic causes. In these cases I have used simplified methods, which, while probably not satisfactory for geodetic purposes, are quite sufficient for geological requirements.

For geologic purposes, we are interested not so much in the actual value of the anomaly at a given station as in the relative value of the anomaly as compared with other stations in the same area. The effect of compensation for distant topographic features, say, beyond 700 km is nearly the same for all stations in an area, say, 200 km in width. Hence the relative values of these stations are affected only slightly by neglecting the effect of distant compensation and topography. Likewise, we can neglect the curvature of the Earth in calculating the effects of topography and compensation out to 700 km without introducing any large error in the relative values of the stations. These simplifications make it possible to compute the isostatic effect for any station in about 15 minutes.

Sedimentary basins--Among the largest of the geologic features are the great sedimentary basins. Most of them are filled with great thicknesses of sediments which are more recent and hence considerably lighter in density than the rocks outcropping on the margins of the basins. If the value of gravity is influenced by the density of the rocks near the station, we should expect to find gravity-minima associated with such basins.

From published pendulum-data I have constructed maps and profiles for a number of basins. Figure 1 is a geologic map of Italy with the Bouguer-anomaly contours drawn according to the pendulum-data. The front of the Apennines is shown as a heavy broken line; geologists tell us that this is an overthrust contact. North and east of the Apennines we have the Tertiary Basin of the Po Valley. It will be noted that the gravity-minimum follows the Apennine front, not the center of the Basin. Figure 2 shows a profile across the same Basin. Here I have calculated an isostatic correction for the Apennines and the Alps, according to the Hayford hypothesis for 100-km depth of compensation. It can be seen that the isostatic correction does not alter the picture greatly except in the vicinity of the Alps. The gravity-picture indicates a considerable deficiency of mass in the area of the Po Valley, and the deficiency seems to extend for some distance under the foot of the Apennines. This could be explained if we assume that the Apennines have been thrust out over the sedimentary basin, and that the deepest part of the basin lies approximately under the edge of the overthrust sheet. Discussion of the magnitude of the anomaly and inferences about the depth of the basin will be postponed until a few more examples have been presented.

Figure 3 shows the gravity-anomaly in the basin-area at the foot of the Carpathians, in Galicia. It will be noted that here, too, the gravity-minimum follows the overthrust at the foot of the mountain. Here we know that the basin extends under the thrust-plate for some distance, as wells have been drilled through the Eocene formations of the foothills into the recumbent folds of the Miocene clays and salt-formations. The left-hand portion of the profile is based upon old stations which seem somewhat erratic; the right-hand portion in the basin is based upon new stations established by the Polish Geological Survey. If we draw an average line through the older stations we have a gravity-difference of about 100 milligals between the highest and lowest portions of the profile.

Now to take a rather long jump from Poland to Wyoming, Figure 4 shows the Bouguer and Hayford isostatic anomalies for the Beartooth-Bighorn Region. The Bouguer anomalies trend downward to the west, but superimposed on this regional gradient we have secondary maxima which agree very well with the structural uplifts. If we assume that the basement-rocks, exposed in these uplifts, have a density of 2.67--the density assumed in calculating the Bouguer anomalies--then we may assume that the anomalies for stations on these uplifts are nearly free from geologic effects; therefore, if we draw a smooth curve through these basement-stations we obtain a regional correction which we may subtract from the Bouguer value to obtain a residual anomaly, which should be due principally to local geologic effects. The regional effect is undoubtedly isostatic; the Bouguer anomalies would seem to indicate that the uplifts are not compensated individually but rather that the Rocky Mountains are compensated as a whole and that the center of the compensation lies somewhere to the west of the Beartooth Range. The residual anomaly-profile which we obtain by this method agrees qualitatively with the geologic structure and is similar in form to the Hayford profile, although the anomalies on the latter are larger in amplitude.

Figure 5 shows the Bouguer and isostatic anomalies in the Caucasus Region. The greatest negative isostatic anomalies are found in the Tertiary basins which flank the Caucasus Range, and the positive anomalies follow for the most part the axis of the Range itself, where denser rocks are close to the Surface. Goubkin [see 1 of "References" at end of paper] gives the thickness of the Tertiary beds of the Apsheron Peninsula (where the isostatic anomaly is -120

milligals) as 4,500 meters; and he estimates that the depth to the crystalline basement is not less than 12,000 meters. The gravity-minimum appears to extend from the Apsheron Peninsula across the Caspian to the oil-field region of Naphtha Dag.

The basins already discussed all contain thick sections of unconsolidated or poorly consolidated Tertiary sediments. It will be interesting to investigate the gravity-situation in some older basins, where the sediments are, as a rule, more consolidated.

Figure 6 is a copy of the geologic map of the Kousnezky Coal-Basin, taken from the guidebook of the Seventeenth International Geologic Congress (1937). The isostatic anomalies have been plotted from Heiskanen's catalog [2]. Only the contours are shown here. It will be seen that there is a fair degree of correlation with surface-geology, although the axis of the gravity-minimum is offset to the west of the axis of the basin, as indicated by surface-outcrops. Also,

Fig. 1

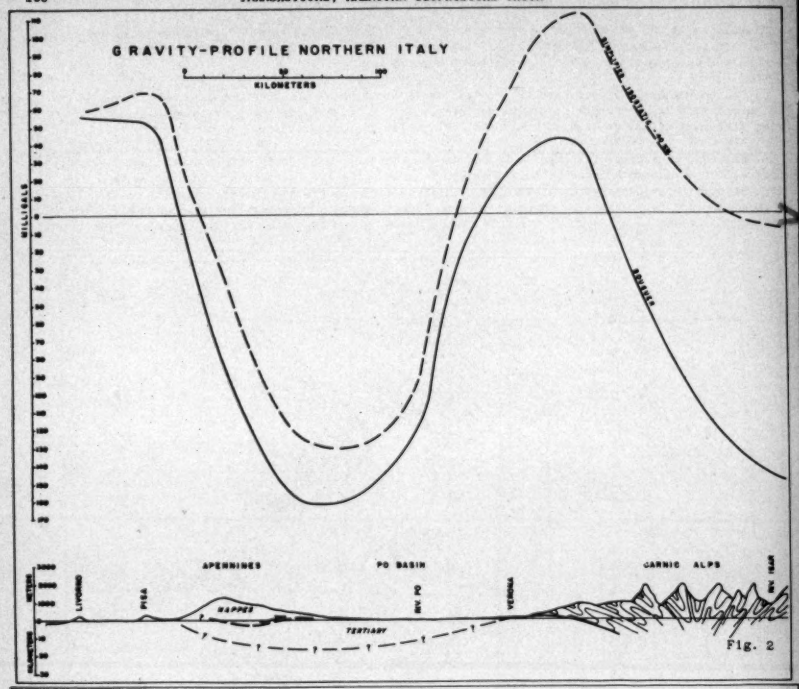

GRAVITY-PROFILE NORTHERN ITALY
KILOMETERS
MILLIGALS
APENNINES
PO BASIN
GARNIC ALPS
LIVORNO
PISA
RIV. PO
VERONA
RIV. ISAR
NAPPES
TERTIARY

Fig. 2

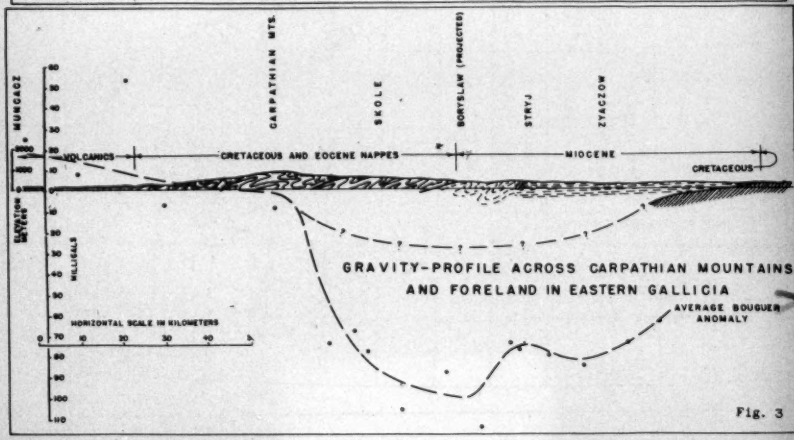
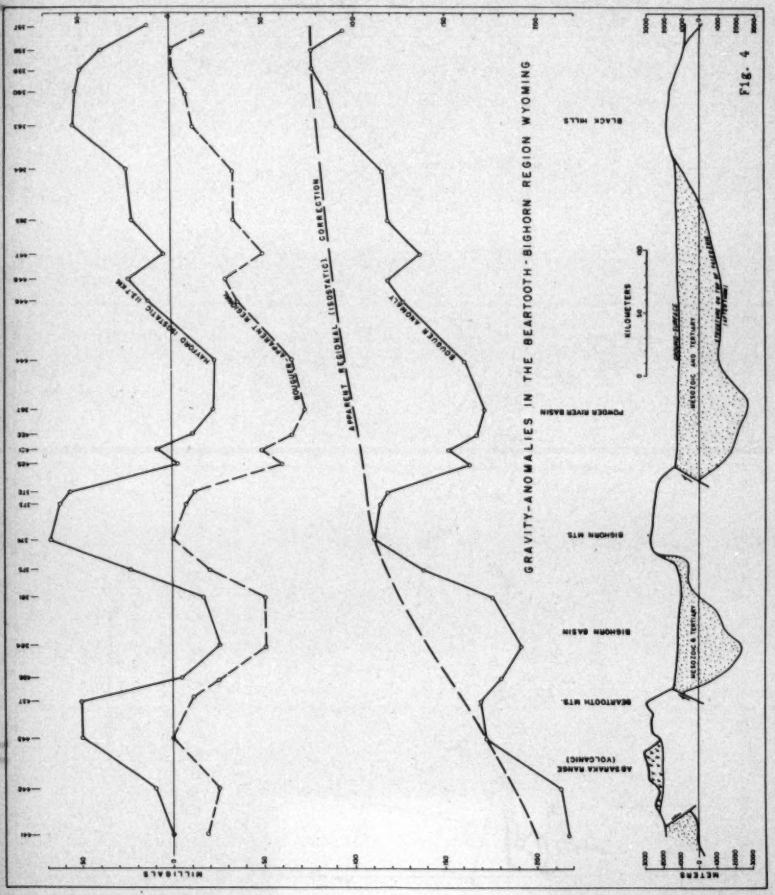
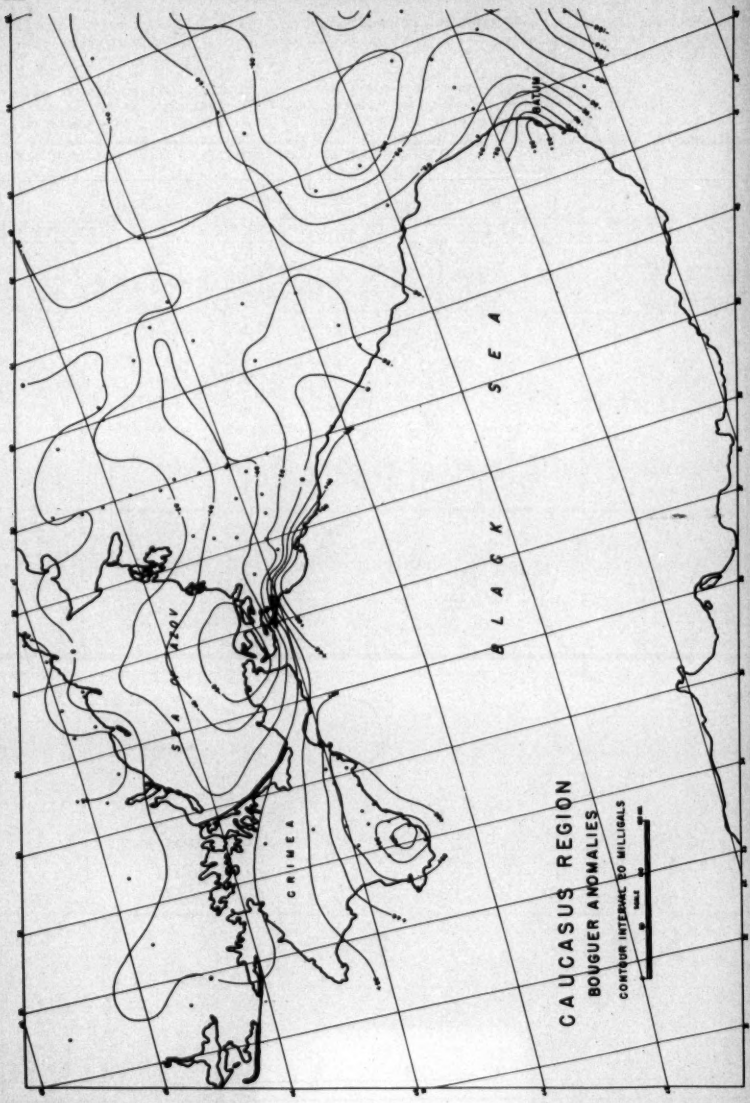

HUNGARY
CARPATHIAN MTS.
BESKID
BORYSLAW (PROJECTED)
STRYJ
ZYDACZOW
VOLCANICS
CRETACEOUS AND EOCENE NAPPES
MIOCENE
CRETACEOUS
MILLIGALS
HORIZONTAL SCALE IN KILOMETERS
GRAVITY-PROFILE ACROSS CARPATHIAN MOUNTAINS
AND FORELAND IN EASTERN GALLICIA
AVERAGE BOUGUER
ANOMALY

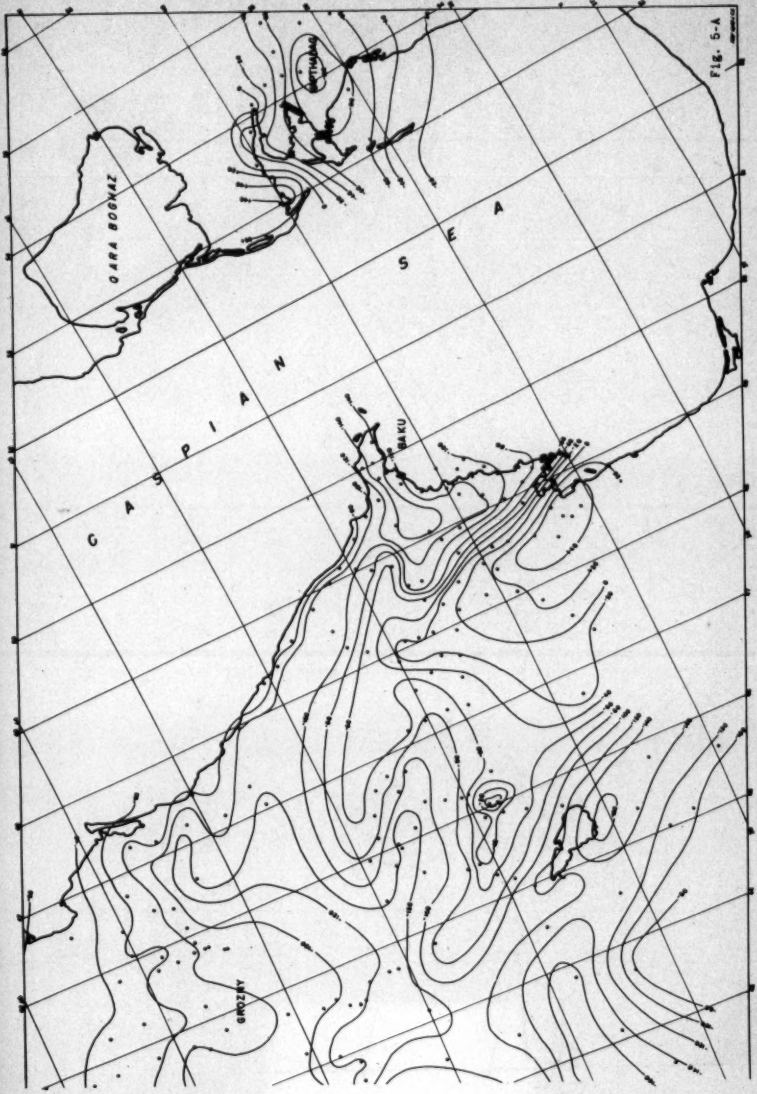
Fig. 3

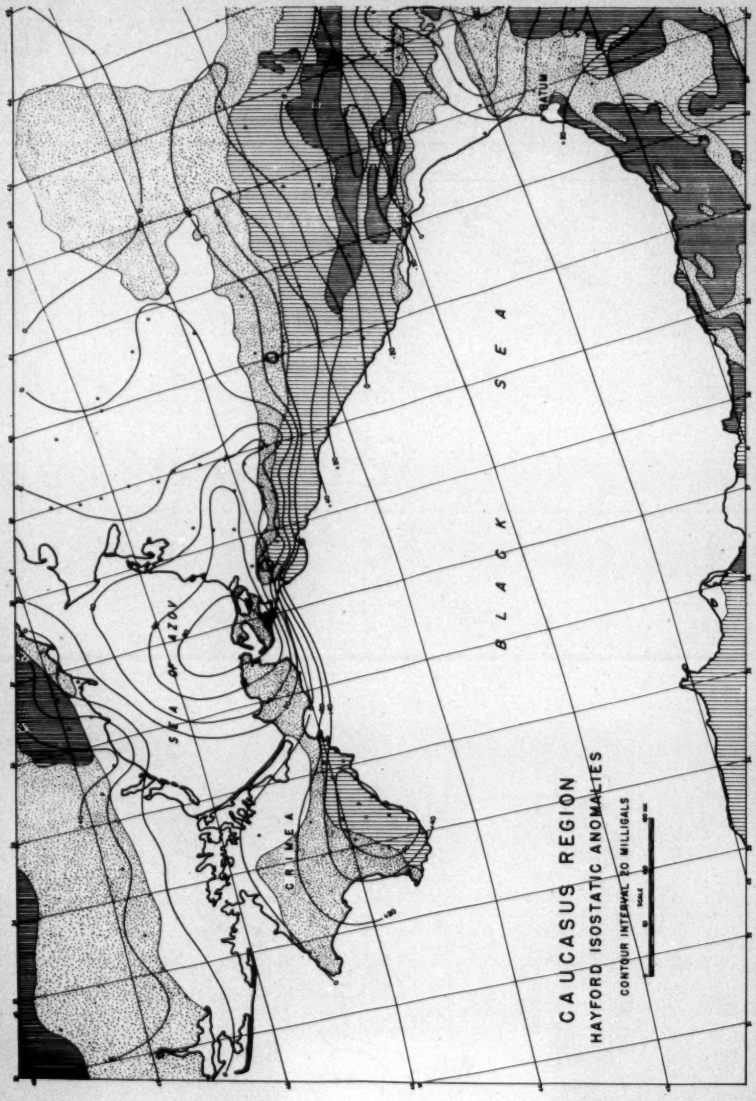
the gravity-anomalies increase more abruptly and attain a much higher value on the east side of the basin than on the west side. The presence of basic igneous rock on the eastern margin may be a key to the explanation.

Figure 7 is a profile across the Ardmore Basin and the Marietta syncline in southern Oklahoma. The geology is from the Oklahoma Survey Bulletin, No. 46, by Tomlinson [3], and from the "Structural map of Texas" by E. H. Sellards [4]; the gravity-data are plotted from a map by Van Weelden [5]. There appears to be good agreement between gravity and geology except at the western end of the profile, where the gravity-values fall off more rapidly on both sides of the Muenster arch than they should to agree with the geologic profile.




BLACK SEA
SEA OF AZOV
CRIMEA
BATUM
CAUCASUS REGION
BOUGUER ANOMALIES
CONTOUR INTERVAL 10 MILLIGALS


KRASNOVODSK
KRASNAYA BOSKAZ
CASPIAN SEA
BAKU
ASTARA
Fig. 5-A


CAUCASUS REGION
HAYFORD ISOSTATIC ANOMALIES
CONTOUR INTERVAL 20 MILLIGALS
0 50 100
BLACK SEA
SEA OF AZOV
CRIMEA
BATUM

LEGEND
ALLUVIUM
TERTIARY
MESOZOIC PALEOZOIC
IGNEOUS AND METAMORPHIC
OIL FIELD
PENDULUM STATION
Fig. 5-B
CASPIAN SEA
KARA BOGHAZ
BAKU
GROZNY

Figure 8 is an east-west profile across the Rhine Valley in the vicinity of Mannheim, and across a part of southern Germany. Only the Bouguer anomalies are shown, but the isostatic correction would not make very much difference, in this region, as far as the relative values of the anomalies are concerned. The Rhine graben is gravitationally low with respect to the horsts of the Vosges and the Black Forest. The Basin also correlates with a gravity low.

Table 1 is a tabulation of the data already presented. The amplitudes of the anomalies on some other basins are also given. Figure 9 gives a comparison of the size and shape of the various minima.

Quantitative considerations--The evidence that we have seen indicates that geologic basins are regions of gravity-minima, whether we use Bouguer or isostatic anomalies. This was to be expected, of course, since the basin-sediments are in general lighter than the surrounding rocks.

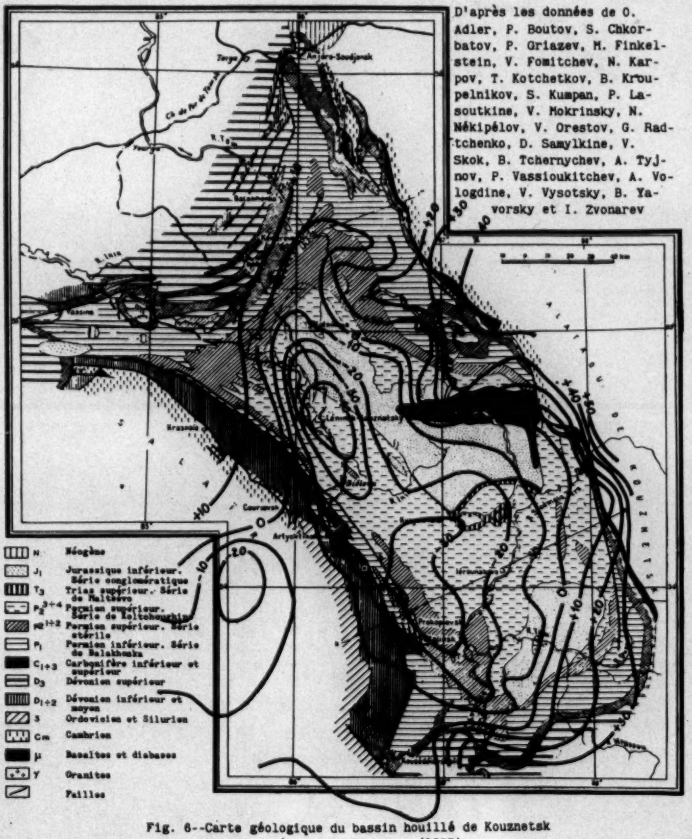

D'après les données de O. Adler, P. Boutov, S. Chkorbatov, P. Griazev, M. Finkelstein, V. Fomitchev, N. Karpov, T. Kotchetkov, B. Kroupelnikov, S. Kumpan, P. Lasoutkine, V. Mokrinsky, N. Nékipélov, V. Orestov, G. Radtchenko, D. Samylkine, V. Skok, B. Tchernychev, A. Tyjnov, P. Vassioukitchev, A. Vologdine, V. Vysotsky, B. Yavorsky et I. Zvonarev
N. Néogène
J1 Jurassique inférieur. Série conglomératique
T3 Trias supérieur. Série de Paltchev
P2+4 Permien supérieur. Série de Kaltchougkir
P2+2 Permien supérieur. Série stérile
P1 Permien inférieur. Série de Balakhonka
C1+3 Carbonifère inférieur et supérieur
D3 Dévonien supérieur
D1+2 Dévonien inférieur et moyen
S Ordovicien et Silurien
Cm Cambrien
μ Basaltes et diabases
γ Granites
Failles

Fig. 6--Carte géologique du bassin houillé de Kouznetsk
Dressée par B. Yavorsky (1935)

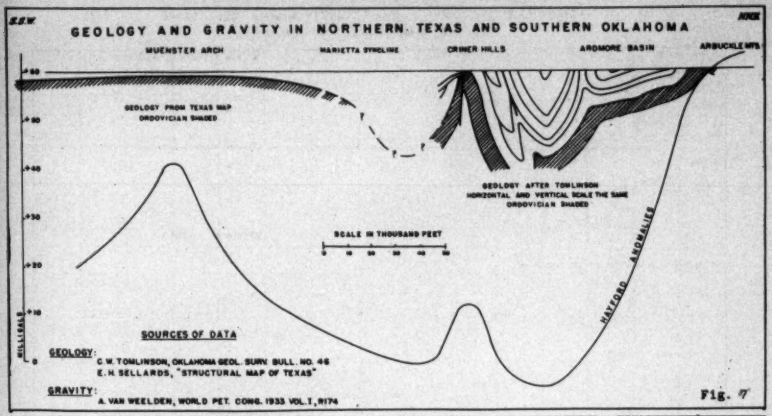


Fig. 7

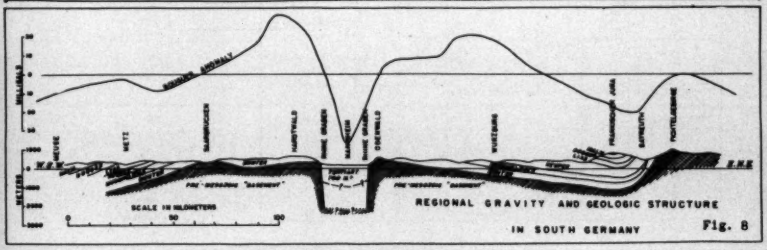


Fig. 8

Table 1--Amplitudes of negative anomalies in sedimentary basins

Location	Bouguer	Isostatic
	mg	mg
Po Valley--Apennines	200	230
Galicia	100	
Apsheron Peninsula	100	180
Bighorn Basin	50	90
Powder River	70	85
Maturin (Venezuela)	150	
Maracaibo (Venezuela)	170	
Texas Gulf Coast	50 (?)	50 (?)
Ardmore (Oklahoma)	75	70
Magdalena (Colombia)	130	
Roumania	110	
Ferghana (Russia)	50	100
Kousnetzky (Russia)		60
Other negative anomalies		
Rift Valley (Africa)	45	75
Rhine Graben	65	
Puerto Rico--Nares Deep		200

It seems natural, therefore, to suppose that we can calculate from the magnitude of the gravity-anomaly the deficiency of mass in the basin. Let us turn our attention to that problem now.

PROFILES OF SOME LARGE GRAVITY MINIMA ALL DRAWN TO THE SAME SCALE FOR COMPARISON

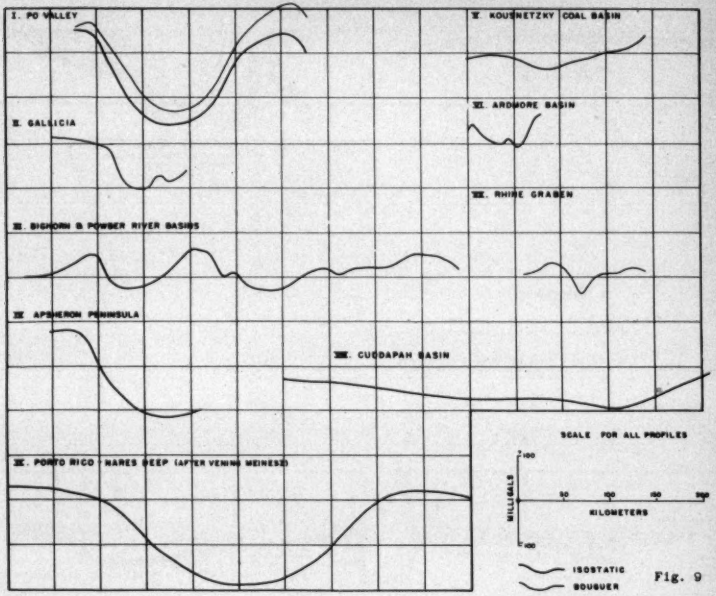


Fig. 9

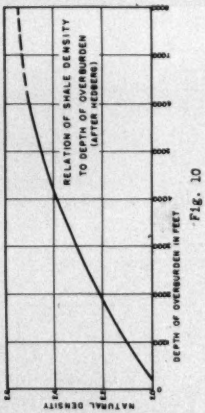
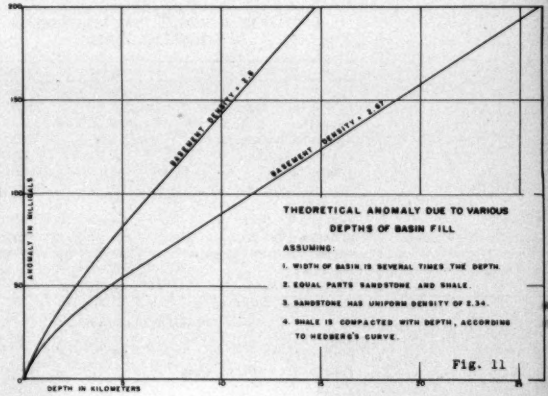


Fig. 10



THEORETICAL ANOMALY DUE TO VARIOUS DEPTHS OF BASIN FILL

ASSUMING:

1. WIDTH OF BASIN IS SEVERAL TIMES THE DEPTH.
2. EQUAL PARTS SANDSTONE AND SHALE.
3. SANDSTONE HAS UNIFORM DENSITY OF 2.34.
4. SHALE IS COMPACTED WITH DEPTH, ACCORDING TO HEDBERG'S CURVE.

Fig. 11

For a station in the center of a very wide basin, gravity should be less than on the edges of the basin by an amount approximately equal to $2\pi k \Delta\sigma t$, where "k" is the gravitational constant, $\Delta\sigma$ is the difference in density between the basin-fill and the surrounding rocks, and "t" is the thickness of the basin-fill. This formula assumes that the effect of the basin-fill is that of an infinite sheet of density and thickness "t", an approximation that is very nearly realized in the center of a wide basin. The expression $2\pi k \Delta\sigma t$ is equal to 42 milligals, when $\Delta\sigma = 1$, and t = 1 km. If $\Delta\sigma = 0.3$, the effect of a kilometer of basin-fill is to produce a gravity-difference of $0.3 \times 42 = 12.6$ mg. Now the gravity-difference between the edges and the center of the Po basin is about 200 milligals, hence with $\Delta\sigma = 0.3$, the depth "t" would have to be $200/12.6 = 15.9$ km, or 52,000 feet, certainly a very large figure. Now if the rocks surrounding the basin are assumed to have a density of 2.67, the basin-rocks would on this assumption have an average density of 2.37.

But what is the density of the basin-fill, actually? I am sorry to say that we do not know. The surface-rocks, which are mostly clays, seem to have a density of about 2.2, but the work of Athy [6] and more recently of Hedberg [7] shows that the densities of clays increase rather rapidly with depth. Figure 10 is Hedberg's curve for the increase of density with the depth of clays and shales based on cores from wells in Venezuela, all of which are in the Tertiary. According to these data, a density of about 2.6 is reached at about 12,000 feet, and the maximum gravitational effect that could be produced by a basin filled completely with shale, no matter what the depth, would be about 50 milligals.

Of course, the basins contain, as well as shale, sandstone and limestone. Sandstones are believed to be compacted only slightly, if at all, with depth; on the other hand, the density of sandstone is quite variable, depending on the porosity and degree of cementation. In the absence of data, let us make some assumptions. Let us assume that the sandstones in the basin have an average porosity of 20 per cent, that the mineral grains have an average density of 2.67, and that the pore-spaces are filled with water; then the effective density of the sandstone is $0.8 \times 2.67 + 0.2 \times 1 = 2.34$ (Ambronn gives 2.3 for the average density of sandstone). Furthermore, let us assume that the basin is filled with alternate beds of sandstone and shale in equal amounts, and that the density of the shale varies with depth according to Hedberg's curve. Then we can calculate the average density for various thicknesses of such a combination and the gravity-defect due to these thicknesses, assuming 2.67 to be the density of the basin. The result of this calculation is shown in Figure 11.

Now let us apply these calculations to some of the basins already studied. In the Po Valley, if we use the isostatic anomalies, we have an amplitude of 220 milligals. From our curve, this would indicate a depth of 29 km--certainly an astounding thickness of sediments. In the Galician Basin the figure is 11.5 km--still a surprising depth.

In the Bighorn Basin, we have accurate determinations of densities of surface-formations, due to Chamberlin and Woollard. Both Chamberlin [8] and Woollard [9] made calculations of the gravitational effect of the sediments, using the best available estimates of the depth to basement, and corrected the isostatic anomalies for these effects; in both cases, there was a considerable residual negative effect for the basins as compared with the adjoining uplifts.

Seven of the basins in Table 1 have anomalies of 100 milligals or more, which, on the assumptions of Figure 10, would indicate depths of over 11.5 km. Are the basins really this deep, or is something wrong in our assumptions? There are at least four possibilities:

(1) The assumptions are essentially correct, and the basins are actually very much deeper than most geologists would postulate. This possibility cannot be ruled out, as long as none of the basins has been drilled actually to basement.

(2) The density 2.67 (average density of granite) is too low for the basement-rocks. The use of the figure 2.8 in the case of the Po Basin, for example, would reduce the calculated depth to 15 km. This explanation would not apply to the residuals found by Chamberlin and by Woollard in the Bighorn Basin, however, where the densities of the basement-rocks were actually determined from outcrops.

(3) The compaction-curves do not apply in all cases. It has been suggested that under conditions of rapid accumulation, water and colloidal materials may be imprisoned in the clays, which might remain porous even at very great depths. It is also possible that in coring and determining densities, there is a tendency to sample the more consolidated and hence denser portions of the section, due to the practical difficulties of recovering cores, and determining specific gravities of unconsolidated material.

(4) The assumptions as to compaction and density of the basement are essentially correct, but the gravity-minimum is due only in part to the light sediments and the residual effect is caused by density-anomalies within the basement.

In connection with this last hypothesis, let us look at one more basin--this time of pre-Cambrian age. Figure 12 is a generalized geologic map of southern India with the Hayford anomalies superimposed. For the most part there seems to be little correlation with surface-geology; but there is one exception--the Cuddapah Basin is neatly outlined by the gravity-contours, although the gravity-basin is somewhat wider than the geologic. The same tning is seen in profile on Figure 13. The Cuddapah sediments, of pre-Cambrian age, which have a thickness of 20,000 feet, have, according to the Indian Geological Survey, a density of 2.7--in fact, a higher density than that of the surrounding basement-complex. There should, therefore, be a gravity high, rather than a low, over the basin. Glennie's explanation [10] of this paradox is shown in the same Figure. He assumes that the downwarp extends for at least 30 km into the basement, which he assumes after Jeffries to be stratified as shown in the diagram. The downwarp of the lighter layers into denser ones would explain the gravity-minimum associated with the basin and

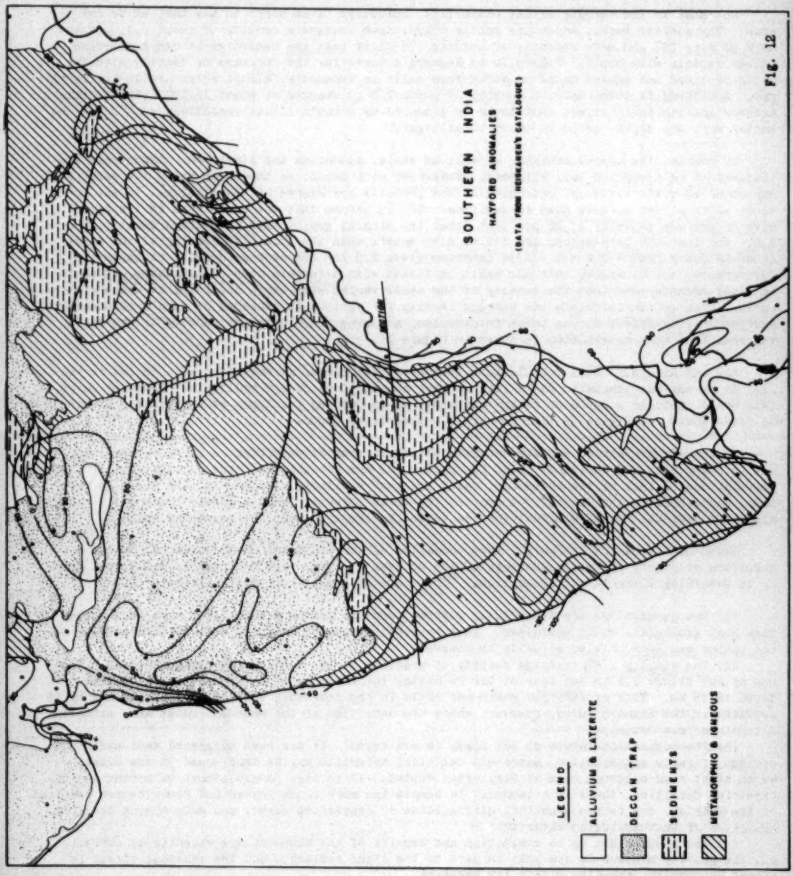
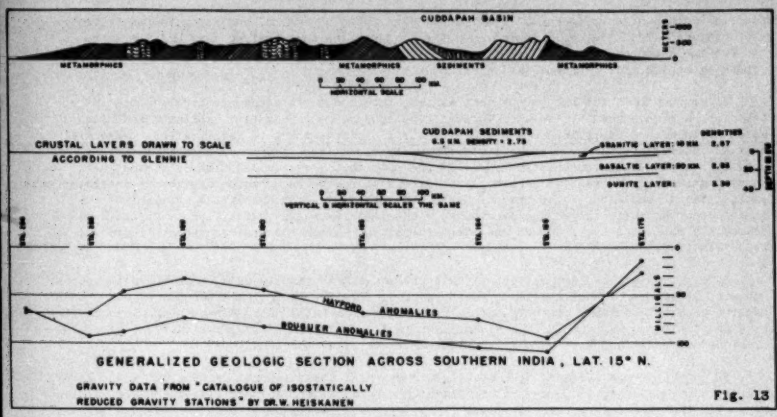


Fig. 12



GENERALIZED GEOLOGIC SECTION ACROSS SOUTHERN INDIA, LAT. 15° N.

GRAVITY DATA FROM "CATALOGUE OF ISOSTATICALLY REDUCED GRAVITY STATIONS" BY DR. W. HEISKANEN

Fig. 13

also the great width of the gravity-minimum as compared with the geologic basin.

Meinesz and Hess [11] have used a somewhat similar hypothesis to explain the negative anomalies found at sea in association with island-arcs and oceanic deeps. They assume a granitic layer 25 km thick, which is buckled down in an isoclinal fold into a peridotitic layer of density 3.3.

If we were to postulate crustal downwarp according to the Glennie hypothesis in the Po Basin, for example, we could reduce the anomaly by about a third, perhaps. We would still have a very deep basin, about 20 km (using 2.67 for the basement-density). Crustal downwarp might also explain the apparent discrepancy between the axis of the Kousnetzky Basin and the gravity-trough, since the folding in the basement-layers need not conform exactly to that in the sediments.

I do not believe that we have enough data at present to say definitely whether or not the major uplifts and downwarps that we see at the surface extend into the crustal layers or to what depth they extend. I do regard the hypothesis as a plausible one, however, and one that seems to reconcile gravity-data with density-determinations and with the geologists' estimates as to basin-depths.

Basins and isostasy--According to the theory of isostasy, columns of equal area, extending from the surface down to the depth of compensation, all have the same mass. The basins that we have examined are (excepting the Cuddapah Basin) regions where the upper portion of the crust is of subnormal density. They are also areas that are topographically lower than their surroundings. Hence, for compensation, there should be material of extra density in the lower part of the column to counterbalance the light material in the upper part. But the ordinary isostatic corrections (whether Hayford or Airy-Heiskanen) make no allowance for density-variations in the upper part of the crust, or for their compensation. If the anomalies in the basin of the Po, for example, contain the effect of heavy material beneath the basin, then the effect of the light material is even greater than the Hayford anomaly shows. The negative anomaly over a basin can be expressed in a simple equation: Let a, b, and c be the numerical values of the anomaly, the basin-effect, and the compensation-effect, respectively, measured at the center of the basin. Then

$$-a = (-b + c)$$

or

$$-b = (-a - c) = -(a + c)$$

that is, the numerical value of the basin-effect is greater than the numerical effect of the anomaly as calculated, by the amount c, the effect of the compensation. Hence we have to reckon on a deeper basin than if we had assumed no compensation. But the basin is already uncomfortably

deep; do we now have to increase this figure? The ratio of c to b, and hence the extra depth that must be calculated, will depend upon the depth of the compensating mass and its width. If the average depth of the heavy material is 50 km, the ratio (c/b) may range from 1/4 to 1/2, depending on the type of compensation assumed.

If we deny that the basins are compensated, then I can see no escape from the conclusion that they are held down by tectonic forces. The occurrence of negative isostatic anomalies in association with rift-valleys, as noted in Table 1, lends support to Bailey Willis' theory of ramp-structure, according to which the downfaulted block is held down by horizontal forces against the isostatic tendency to rise. If the ramp-theory be correct, the crust must still be under considerable tangential stress. Such stress operating in a region already depressed by an excess load of sediments would produce further downwarping. The association of most of the basins described with folded and overthrust mountain-belts suggests that the same forces which folded the mountains and produced the overthrusts also shaped the basins, and still operate to hold them in place.

Conclusions and recommendations--I have presented some gravity-data, none of which is new, but most of which have not previously been examined from the geological standpoint. I have attempted to point out some of the possible inferences from these data. In closing, I would like to emphasize that they are inferences only, and not conclusions. I believe that definite conclusions must wait until we have more data, particularly of three sorts:

(1) Gravity-data--We need more gravity-surveys like those recently conducted by the United States Coast and Geodetic Survey on the Atlantic Coastal Plain, where stations are spaced closely enough that accurate gravity-profiles may be drawn. Gravity-data on old, worn-down basins where the densities can be determined should give evidence either for or against deep crustal warping. Data on the Basin and Range province and profiles across the Rockies in various latitudes would give additional data on the nature of isostasy.

(2) Density-determinations--This is one of the most neglected provinces of geology. Geological reports give descriptions of rocks by color, texture, structure, and chemical composition, but seldom does one find any mention of specific gravities.

(3) Seismic data--The seismologist is already giving us data on the depth and structure of basins; more such data would be extremely helpful, particularly when combined with density-determinations, in calculating what part of an anomaly, if any, must be assigned to deep crustal warping. We also depend upon the seismologist for information as to the depth and, if possible, the shape of the various surfaces of discontinuity within the crystalline basement.

I am indebted to the officials of the Standard Oil Company of New Jersey for permission to publish this paper.

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Standard Oil Company of New Jersey,
New York, New York

THEORY AND OPERATION OF THE PHOTOGRAPHIC REFLEX ZENITH-TUBE

Paul Sollenberger
(Published with the approval of the Superintendent, U. S. Naval Observatory)

The photographic zenith-tube has been in use at the United States Naval Observatory since 1915 for the determination of the variation of latitude, and since 1934 for the determination of

time. The latitude-observations are used in the reduction of the work of the meridian instruments at the Observatory, and the time-determinations are used for the transmissions of time-signals. The instrument has been described elsewhere, but its construction and use are probably not generally understood. Since special studies based upon observations taken with the zenith-tube are now being made, it is believed that a discussion of the instrument is desirable.

Fundamentally the photographic reflex zenith-tube consists of an objective, a photographic plate, and a mercury basin. The axis of the objective is vertical. The plate is mounted, emulsion-side down, in a carriage which may be driven along a horizontal track just below the objective. The objective, track, and plate-driving mechanism may be rotated as a unit through 180° about a vertical axis. This rotation is called "reversal" and the assembly which is reversed is called the "rotary". The mercury basin is placed beneath the rotary at such a distance that the light from the star will come to a focus on the plate after passing through the objective and being reflected from the mercury. The instrument should be so constructed that the second nodal point of the objective will be at the intersection of the axis of reversal and the plane of the photographic emulsion.

According to the principles of optics an objective has two nodal points. A ray of light which approaches the objective directed toward the first of these points will, after emerging from the objective, be directed away from the second point and parallel to the entering ray. This principle is based on the assumption that the objective forms perfect images and has a linear scale-value throughout the field of view. In the case of an imperfect objective the rays which emerge parallel to their direction of entry are not directed away from a common point. However, if the objective is of good quality and the field of view is small, the rays will pass within a small fraction of an inch of a common point.

The importance of these facts will be better understood by consideration of an ideal case. Let us suppose that an infinitely distant star appears in the zenith. Let us also assume that the plate-carriage does not move on the track, so that the intersection with the axis of reversal will be a fixed point on the sensitive emulsion. The rays of light coming from the star will all be vertical, and the ray emerging from the second nodal point will therefore be vertical also. That is to say, it will be normal to the mercury surface. If it were not eclipsed by the photographic plate, that ray would be reflected back along its own path, and come to a focus with the other rays from the star. The image of the star therefore lies somewhere along the line passing through the second nodal point which is normal to the mercury. If the second nodal point lies in the plane of the photographic emulsion and if the instrument is in focus, the image will be at the second nodal point. This is true without regard to the orientation of the rotary. The position of the image on the plate will therefore be unchanged if the rotary is reversed. It can readily be seen that this will be true even though the axis of reversal is not vertical. In fact, the rotary may be rotated about an axis passing through the second nodal point in any direction without displacement of the image on the plate, provided the image is not carried out of the useful field of view of the objective. It therefore follows that flexure of the tube which supports the rotary will not affect the position of the image.

Now if the star is not in the zenith its image will not be formed at the nodal point. When the rotary is reversed the plate will be rotated around the nodal point, but the image will not move with it. The image will therefore describe an arc of a circle on the plate. The radius of that arc multiplied by the scale-value of the plate will give a measure of the zenith-distance of the star.

In the case of the Naval Observatory instrument Dr. Frank E. Ross [Latitude observations with the photographic zenith tube at Gaithersburg, Maryland, by Frank E. Ross, in cooperation with the International Geodetic Association, Spec. Pub. No. 27, U. S. Coast Geodetic Survey] concluded that the distance between the nodal point and the photographic emulsion did not exceed one millimeter. This amount would cause an error in the measured zenith-distances of about $0.0002\,\theta$, where θ is the angle between the axis of rotation and the vertical. In practice this angle does not exceed 20 seconds of arc, so that the resulting error is not more than 0.004 second. The errors resulting from the fact that the nodal point does not lie on the axis of reversal, from the fact that the emulsion does not lie in the focal plane, and from the imperfections of the objective are all of smaller amount than the quantity given above. A more complete discussion of the errors will appear in a future publication of the Naval Observatory.

So far the discussion has been based on the supposition that the star does not move, while in fact the stars pass across the field from east to west. The plate-carriage is driven along a track at a speed equal to that of the motion of the star's image, so that point-images are secured on the developed plate. Four exposures are taken on each star, each of 20 seconds' dura-

tion, and there are ten-second intervals between exposures. The rotary is in one position during the first and third exposures, and in the reversed position during the second and fourth exposures. Although the carriage is always driven from west to east during exposures, its direction of motion with respect to the track changes every time the rotary is reversed. The plate is therefore driven over a certain section of the track during one exposure, and then driven backward over the same section during the next exposure. The times at which the plate passes certain fixed points are recorded on a chronograph by means of a contact mechanism. The exact position of the contact-points is unimportant so long as they are the same when the carriage moves in either of the two directions. It travels over the same portion of the track and in the same direction during the first and the third exposures. The difference in the position of the first and third images on the plate is due to the motion of the star in the interval between exposures. The same is also true of the second and fourth images. These pairs of images lie along east-west lines; therefore, they enable one to orient the plate for measurement. The scale-value of the plate is determined by measurement of the distance between the images of any one pair, which corresponds to one minute of time. The distance in the declination-coordinate between the images of one pair and those of the other pair corresponds to twice the zenith-distance of the star in declination. Likewise the distance between the pairs of stars, measured in right ascension, gives twice the correction to be applied to the mean clock-time of the exposures in order to secure the clock-time of meridian transit.

It is interesting to note that many of the errors and corrections which are incident to time-determinations with transit-instruments are eliminated with the zenith-tube. The level is automatically established by reflection from the mercury surface. The flexure of the telescope tube is without appreciable effect. The only personal equation is that of measuring the plate, which is negligible. The necessary information as to the scale-value and azimuth are provided by the images of each star.

Excepting the personal equation, the same advantages also apply to the work in declination. Other types of instruments used for the determination of the variation of latitude are subject to the effects of tube-flexure, and most of them require the measurement of levels.

It should be borne in mind that the photographic zenith-tube is adapted only to the measurement of latitude and time, and not to general star-position work. It is therefore not to be regarded as a competitor with the meridian-transit circle, or with other instruments used in position-work.

So far our discussion has been confined to the theoretical advantages of the instrument. It will be of interest to note the actual results secured. The probable error of a time-determination made with a single star, determined by comparison with other stars taken on the same night, is $\pm$0.0095 sec. This corresponds to $\pm$0.114 second of arc. The probable error of a determination of latitude with a single star is $\pm$0.104 second of arc. The slightly larger error in right ascension is probably due to the error in timing the exposures. The probable error of a time-determination on a single night, as judged by comparison with results secured on other nights, is $\pm$0.0044 second of time. This last error includes not only the error of the time-determination but also the error of the clock-rates.

The instrument has one rather severe limitation in that it makes possible the observation of only those stars which are located so that they pass within ten minutes of arc of the zenith. The total number of stars available for use in this latitude do not exceed two hundred. However, this limitation is not without compensations. The same star-lists are observed night after night and year after year, with the result that a very valuable mass of precise observational data is collected. These data are useful for the study of astronomical and geodetic problems, as is shown by another paper which is being presented to the American Geophysical Union today.

One point of particular interest which has been brought out in discussing the observations with the zenith-tube is the close agreement between the distribution of errors given by the observations and the probability-curve. Table 1 illustrates this very well. Two groups of stars are observed on a clear night, and the error of the latitude indicated by either group may be judged by comparison with the other group. Since the errors so obtained are larger in some seasons than in others, the results have been collected in three columns. The columns headed "O" give the percentage of errors which fall in various ranges, while the columns headed "C" give the percentages required by the probability-curve.

The agreement between the observed and computed values is so close as to be a source of considerable satisfaction. It shows that, at least under ideal conditions, the probability-curve gives a good representation of the distribution of errors. It also shows that our work is

Table 1

Season	Fall and winter		Spring		Summer	
Number of nights	900		600		900	
Probable error	±0.060		±0.063		±0.052	
	O	C	O	C	O	C
0.00 - 0.06	50.8	50.0	48.2	47.9	57.7	56.2
0.06 - 0.12	28.5	32.3	32.4	32.1	29.1	31.9
0.12 - 0.18	13.7	13.4	13.2	14.6	10.1	9.9
0.18 - 0.24	4.9	3.6	4.2	4.4	2.3	1.8
0.24 - 0.30	1.9	0.6	1.4	0.9	0.4	0.2
0.30 - 0.36	0.2	0.1	0.4	0.1	0.3	0.0

not affected by large or erratic errors. There is a slight excess of the larger errors, but the difference between the number of errors in excess of four times the probable error and the number indicated by the curve is less than one per cent of the total number of errors.

It is unfortunate that the Naval Observatory instrument is the only one of its kind in use. Another instrument of the same type would be very useful, especially if the two zenith-tubes were located so that their work could be compared. It is hoped that institutions which contemplate erecting instruments for the determination of time or latitude will give careful consideration to the possibilities of the photographic reflex zenith-tube.

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EFFECT OF THE MOON IN THE DETERMINATION OF LATITUDE AT WASHINGTON

Wm. Markowitz and S. M. Bestul
(Introduced by P. Sollenberger)
(Published with the approval of the Superintendent, U. S. Naval Observatory)

Abstract

Observations taken with the photographic zenith-tube of the United States Naval Observatory for the determination of latitude during the 24-year period 1915.9 to 1939.9 were examined for lunar terms. The effect of the Moon was assumed to be

$$\Delta\varphi = A_2 \cos 2t + B_2 \sin 2t + A_1 \cos t + B_1 \sin t \qquad (1)$$

where $\Delta\varphi$ is the effect on the observed latitude, t is the Moon's hour-angle, and A_2, B_2, A_1, B_1 are constants to be determined.

Two groups of eight stars each are normally observed in one night. Let

$$\Delta^2\varphi = \Delta\varphi(\text{early}) - \Delta\varphi(\text{late}) \qquad (2)$$

Then it can easily be shown that

$$\Delta^2\varphi = 2 \sin 2\,d(A_2 \sin 2t - B_2 \cos 2t) + 2 \sin d(A_1 \sin t - B_1 \cos t) \qquad (3)$$

where t is the Moon's hour-angle at the mean time of the groups, and 2d is the change of hour-angle between the groups. This latter quantity is a known constant for each pair of groups, and averages three hours. $\Delta^2\varphi$ is the observed difference in latitude for the two groups. It is seen that the equation of condition (3) does not require the latitude to be known at all.

To simplify the computations the residuals were grouped into 24 zones of t, and five zones of lunar declination. A total of 35,000 star-observations, taken on 2,414 nights, was used.

Considerable attention was given to the determination of probable errors. The distribution of the residuals $\Delta^2\varphi$ was found to be very nearly that of the normal law of error. The probable error of a residual is ±0.06.

The residuals were analyzed for the lunar terms in several ways: (a) For short periods of 4, 4, 4, 6, and 6 years; (b) for each of eight pairs of groups (this gives determinations for

eight divisions of the year); (c) for five zones of lunar declination (the results for this case are given as an illustration).

Table 1--Example of case (c)

δ	A_2	B_2	A_1	B_1
+28°, +20°	+0".0135	+0".0052	+0".0054	+0".0105
+20 , + 7	+0.0093	+0.0037	+0.0074	-0.0068
+ 7 , - 7	+0.0026	-0.0022	+0.0061	-0.0033
- 7 , -20	+0.0149	+0.0057	-0.0083	-0.0037
-20 , -28	+0.0103	-0.0035	+0.0017	+0.0206

A_2 and B_2 each have a probable error of $\pm 0".0029$; A_1 and B_1, $\pm 0".0052$.

It was found that for all cases treated the observed coefficients were close to the theoretical coefficients, and the discrepancies were such as would be expected by the theory of probability.

The combined data were solved by least squares. The result is

$$\Delta\varphi_1 = +0".0095 \cos 2t + 0".0014 \sin 2t + 0".0018 \cos t + 0".0016 \sin t \qquad (4)$$

The probable error of each of the first two coefficients is $\pm 0".0013$; that of the latter two is $\pm 0".0023$. The theoretical value of $\Delta\varphi$ for an elastic earth in which there is no tidal lag is [see 1 of "References" at end of paper]

$$\Delta\varphi_2 = +0".0077(1 + \xi) \cos 2t - 0".0054 \sin t \qquad (5)$$

The sin t term is an aberration-term due to the revolution of the Earth around the center of gravity of the Earth and the Moon. Geophysicists [1] estimate that ξ, which depends upon the elastic properties of the Earth, lies between 0.1 and 0.2.

The gravitational attraction of tides in the Potomac, Chesapeake Bay, and a 1,500-mile square basin of the Atlantic was computed. This effect on the observed latitude is

$$\Delta\varphi_3 = -0".0012 \cos 2t - 0".0008 \sin 2t \qquad (6)$$

These terms are to be subtracted from $\Delta\varphi_1$ to compare with the theoretical expression $\Delta\varphi_2$.

The effect of eliminating all residuals $\geq \pm 0".24$, which is four times the probable error, was investigated. There were 39 such residuals out of 2,414, while only 19.7 are expected on the basis of probability. If the large residuals are given zero weight, the change in $\Delta\varphi_1$ is

$$\Delta\varphi_4 = -0".0014 \cos 2t + 0".0005 \sin 2t + 0".0011 \cos t + 0".0005 \sin t \qquad (7)$$

If these residuals are given half-weight, then the change is half that of (7).

We conclude from these results that:

(1) The change in the observed latitude at Washington caused by the Moon is that predicted by theory within the errors of observation.

(2) The Earth's crust at Washington is not subject to short-period deformations of abnormal amplitude.

Similar results for the other coordinate have been obtained previously at Washington [2].

This paper will be published in full in the Astronomical Journal.

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ANALYSIS OF CIRCLE-GRADUATION ERRORS

C. A. Whitten

For the past several years the circles used in the theodolites of the United States Coast and Geodetic Survey have been graduated by the National Bureau of Standards. After being graduated, these circles have been thoroughly tested at the Bureau of Standards and found to have the necessary precision. However, after the circles have been placed in instruments and used in the field the apparent positions of the graduations as seen in the micrometer have sometimes changed. This may be due to a lack of parallelism between the plane of the circle and the plane of the micrometers, to a warping of the circle so that it no longer is an optical flat, or to the metal itself flowing with age. This present discussion considers only the apparent position of the graduations as observed by micrometers with the circle in its normal position in the theodolite.

These apparent errors of graduation may be divided into two classes, accidental and systematic. The former can not be determined except by an examination of each graduation. The latter can be adequately determined with considerably less effort. A carefully planned set of observations, employing the direction-method, will use certain sections of the circle in several different combinations, thus offering possibilities of an analysis. However, when observational data are to be analyzed by mathematical processes careful consideration must be given to the selection of the method of adjustment or curve fitting to be used.

The United States Coast and Geodetic Survey has a room especially fitted with collimators for the testing of theodolite-circles. Figure 1 shows the spacing of the collimators used in a routine test for circle-error. The approximate directions are: A = 0°; B = 67°; C = 106°; D = 146°; E = 213°. The position-settings of the horizontal circle are also shown. The angle between these settings is approximately 1/16 of 180°. The broken lines completing the diameters represent the section of the circle used by the "B" micrometer which is spaced 180° from the "A". A complete set of 16 positions with directions to the five collimators furnishes sufficient data for a very thorough study of the systematic errors.

Heuvelink [see 1 of "References" at end of paper], Wild [2], and Rannie [3] have devised different methods of analysis. However, none of these methods can be readily applied to an abstract of directions observed in the field. For this reason an approximate method of analysis was devised a few years ago. The method was based on the fact that the sum of all the errors is equal to zero and that the sum of the errors at a finite number of points, such as A, B, C, D, and E (Fig. 1), would approach zero as a limit. A first approximation is obtained by setting the sum of the five errors equal to zero. The first step in this method is the determination of the residuals based on the mean directions for the complete set of 16 positions. The second step is the computation of a correction to be placed on the initial direction and added to the residual of each direction for a given position-setting. This correction is equal to the sum of the residuals for the given position-setting divided by the number of directions observed. After this correction has been applied the sum of the corrected residuals for each position will be equal to zero. It is necessary to compute 16 of these corrections, one for each position. These corrected residuals are then plotted with the algebraic value of the residual as one coordinate and the part of the circle actually read in the micrometer as the other coordinate. All values between 180° and 360° are combined with the section from 0° to 180°. This is possible since all values used are the mean of two readings taken 180° apart. In the standard test made by the United States Coast and Geodetic Survey there are 80 such values to be plotted. After the values have been plotted a mean line may be determined for the group. The mean line represents the mean error of two halves of the circle. Any set of observations taken in the standard method would be affected by this mean error. This method may be applied to any set of observations taken in the field. Also if the error of the circle is to be determined for the entire 360°, the individual micrometer-readings may be corrected for the eccentricity of the circle as determined by internal evidence. These corrected readings may be analyzed by the method given above.

Recently another method for determining the systematic errors of a circle has been devised. Corrections to the diameters of the circle representing position-settings as shown in Figure 1 are considered as unknowns. These 16 unknowns represent the systematic errors of graduations. It will be noted from Figure 1 that when "A" coincides with 1, "B" coincides with 7, "C" falls midway between 10 and 11, "D" coincides with 14, and "E" coincides with 4. For each successive position-setting these coincidences will also advance. These coincidences should not be exact in that identical graduations are observed. They should be approximate so that as large a number of graduations as possible will be tested for a small arc of the circle. This is necessary in order to eliminate any effect due to accidental errors of graduation. From a complete set of 16 positions with observations on five collimators, 80 observation-equations may be written using

Fig. 1

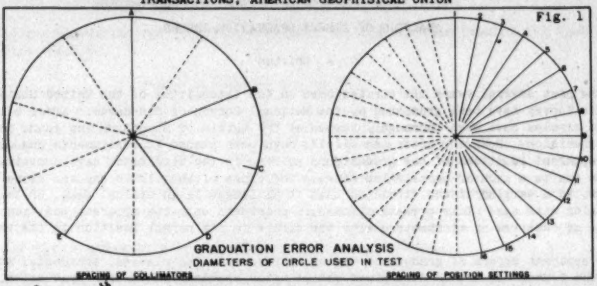
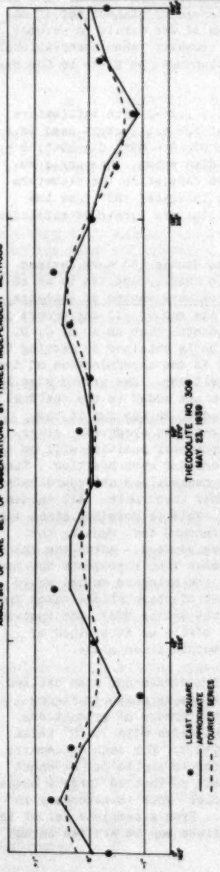


Fig. 2



the 16 unknowns. A least-square adjustment of these observation-equations will give the most probable value for the unknown. This is a rather tedious computation, but it is possible to determine a set of factors which may be used and thus greatly reduce the amount of computation necessary. Due to the symmetry of the 16 normal equations derived from the 80 observation-equations, a set of 16 factors may be computed. These factors represent the accumulated effect of all the normal equations on the unknown for a given normal equation. If the observed quantities are represented as "η's", the factors as "F's", and the unknowns as "C's", the following equations result:

$$(1) \quad C_1 = \eta_1 F_1 + \eta_2 F_2 + \eta_3 F_3 \cdots\cdots + \eta_{16} F_{16}$$
$$(2) \quad C_2 = \eta_2 F_1 + \eta_3 F_2 + \eta_4 F_3 \cdots\cdots + \eta_1 F_{16}$$

$$(16) \quad C_{16} = \eta_{16} F_1 + \eta_1 F_2 + \eta_2 F_3 \cdots\cdots + \eta_{15} F_{16}$$

For all observations made in the testing room of the United States Coast and Geodetic Survey where the directions to the collimators are fixed, these factors will remain constant. The sum of the 16 "C's" should equal zero. This serves as a check for the computation.

Figure 2 shows the analysis of the circle in theodolite No. 308. Three different methods were applied to the observations. Heuvelink's method was modified slightly but the fundamental principle of the use of Fourier series was retained. Since the maximum range of the mean curves is less than two seconds, the circle may be expected to give excellent results in field-use. Ordinarily the circles are analyzed by only one method--the approximate--but in this particular case a comparison of results as given by different methods was desired.

Figure 3 shows the analysis of circle No. 22 with tests at intervals of six months. When the circle was graduated in 1933 the test made at that time indicated the maximum range of error to be less than two seconds. Since that time changes have taken place in the apparent position of the graduations. Two of the tests were made on the same day, May 11, 1939, by two different observers. The sharp systematic features of the curves are present in all of the four tests. These observations were also analyzed by the least-squares method. From a study of these values it will be seen that the approximate method may not reveal the maximum error present as indicated by the least-squares method. If the errors of the circle were as systematic and symmetrical as a sine-curve the values determined by the two methods would be identical and would reproduce the sine-curve, but with the errors distributed as these tests indicate, there is a difference in the results obtained by the two methods. The errors

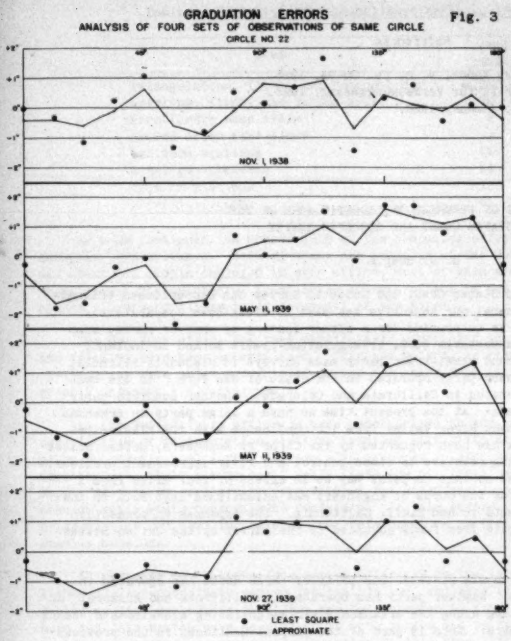


Fig. 3

of the circle were so large that it was necessary to have it regraduated.

Figure 4 shows the comparison of two tests also shown in Figure 3. The purpose of this comparison is to show what order of accuracy might be expected in determining circle-graduation errors. One test was made in the morning and the other in the afternoon of May 11, 1939. Observing conditions were practically the same. As stated before, each test was made by a different observer. The difference of the two methods is again apparent. However, for circles which are more precise and have a smaller range of error, the two methods give a closer agreement.

Either of the methods discussed here determine the circle-graduation errors with sufficient accuracy to study any changes that may take place in the instrument. The present program of the Survey calls for a periodic testing of the theodolites and their circles. In this way it is possible to maintain a high degree of precision in the field-work and when difficulties with an instrument do arise, the circle can be tested and regraduated if necessary.

The author wishes to express his appreciation to members of the Division of Geodesy, especially to J. A. Duerksen, who have given valuable suggestions and assistance in the development

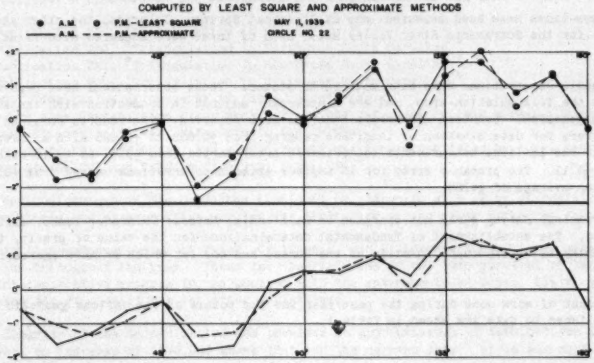

CIRCLE GRADUATION ANALYSIS
COMPARISON OF TESTS MADE BY TWO OBSERVERS ON THE SAME DAY
COMPUTED BY LEAST SQUARE AND APPROXIMATE METHODS
A.M. P.M.—LEAST SQUARE
A.M. P.M.—APPROXIMATE
MAY 11, 1939
CIRCLE NO. 22

Fig. 4

of these methods of analysis.

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U. S. Coast and Geodetic Survey,
Washington, D. C.

ANNUAL REPORT OF PROGRESS OF GEODETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY

H. W. Hemple

During the past year the United States Coast and Geodetic Survey has accomplished triangulation-surveys in 15 States. In general our objective has been to break down comparatively large nets of horizontal control so as to provide for a closer spacing of arcs of survey-monuments. One party operating with the portable steel triangulation-towers worked in Indiana, Ohio, Kentucky, and Maryland. A second steel-tower party made surveys in Missouri, Illinois, Wisconsin, and Michigan. A third tower-party operated in the State of New York. In the west one mountain triangulation-party operated in California and Colorado. Another mountain party operated in Nevada, Idaho, and Montana. At the present time we have a large party in Arkansas establishing control along the Arkansas River Valley from its confluence with the Mississippi River to Tulsa, Oklahoma. This work has been requested by the Corps of Engineers, United States Army, for use in surveying and mapping relative to flood-control and river-improvement problems. Detailed control is being established so that no point may be in excess of four miles from a control-monument. Similar control for the Corps of Engineers was established last fall in the Sacramento River Valley from Sacramento to Red Bluff, California. The expenses in connection with both these projects have been paid from funds advanced to the Survey by the United States Army.

Leveling has been accomplished in six States. One party of three units has operated in Colorado, Nebraska, and South Dakota. Another party has operated in California and Arizona. At present we have a level-party operating along the Arkansas River establishing elevations of bench-marks for use of the Corps of Engineers. This is part of the project mentioned in the previous paragraph for which the United States Army is furnishing the necessary funds. In general our objective in the leveling program has been to obtain lines of leveling, the accomplishment of which will permit of regional adjustment of elevations.

We have also established aeroplane-record courses of three km, 50 km, and 500 km for Wright Field at Dayton, Ohio, and Lowry Field at Denver, Colorado. These courses were determined at the request of the United States Army Air Corps for use in speed-tests of airplanes.

Two base-lines have been measured--one at Steamboat Springs, Colorado, the other at Orland, California--for the Sacramento River Valley arc. Both of these were measured with first-order accuracy.

Astronomic observations have been made in 13 States. These observations have been made at stations on the triangulation-arcs, and are a necessary adjunct in connection with the adjustment of the triangulation. Fourteen astronomic stations were observed. The results obtained give probable errors for determination of longitude ranging from $\pm 0^s.002$ to $\pm 0^s.025$ with an average of $\pm 0^s.013$. For the latitude-measurements the probable error varied from $\pm 0''.07$ to $\pm 0''.18$ with an average of $\pm 0''.11$. The probable error for 16 Laplace azimuth-observations varied from $\pm 0''.21$ to $\pm 0''.35$ with an average of $\pm 0''.28$.

A gravimetric survey-party has operated in California, Nevada, Colorado, Idaho, Illinois, and Maryland. The establishment of fundamental determinations for the value of gravity throughout the country is an important function of the Bureau and one for which we have increasing demands.

The amount of work done during the past year and the totals of the various geodetic activities accomplished to date are shown in Table 1.

Table 1--Geodetic work accomplished April 1, 1939, to March 31, 1940

Item	Completed 1939-1940	Total to date
Triangulation, first- and second-order	4,200 miles	79,200 miles
Leveling, first- and second-order	1,700 miles	273,700 miles
First-order base-lines	2	212
Second-order base-lines	..	54
Latitude-stations	14	854
Longitude-stations	14	705
Azimuth-stations	12	1,168
Gravity-stations	61	1,081

We have continued the sponsorship of the computing offices in New York, New York, and Philadelphia, Pennsylvania. Both of these are projects of the Work Projects Administration. There are about 175 people employed in each office, most of whom are obtained from the rolls of the unemployed. The successful functioning of each office is due to adequate supervision being furnished by permanently employed personnel of the Bureau.

The New York office has been particularly beneficial in that adjustments of triangulation and leveling have been accomplished. This has materially reduced the large amount of unprocessed field-survey data which accumulated during the years from 1933 to 1936 when we were engaged on a greatly expanded field-program.

In the Philadelphia office we have concentrated on the preparation for lithoprinting of descriptions of triangulation-stations together with lists of geographic positions and lists of plane-coordinate positions. We have also prepared in like manner descriptions of bench-marks together with their elevations. While these are not final publications, they do give a means of supplying data in preliminary form without the attendant recourse to photostating original records which would otherwise be necessary. In this office also we are preparing indices of triangulation and leveling data so that references to particular stations or bench-marks may be readily obtained.

In response to requests from survey officials on the Island of Puerto Rico we have established a plane-coordinate system for that Island, and have issued the necessary projection tables so that geographic positions may be converted to plane coordinates. The units of measurement for this system have been given in both meters and in feet. The system adopted is on the Lambert projection and the scale-correction is less than 1/50,000 for the entire Island.

Publications of control-data issued or in process of printing during the past year are as follows:

Special Publication 214, "First and second order triangulation in Michigan."
Special Publication 217, "Geodetic operations in the United States, 1936-38."
Special Publication 218, "First and second order triangulation and traverse in North Carolina," Vol. 2.
Special Publication 219, "Triangulation in New Mexico."
Special Publication 220, "Triangulation in Northwest South Carolina."
Special Publication 221, "Triangulation in Southeast South Carolina."
Special Publication 222, "Triangulation in Northeast South Carolina."
Serial 624, "Computation of traverse by plane coordinates."
Issued by the Army Reproduction Plant from surveys and data made by this Bureau, "Triangulation along the Mississippi River, Vicksburg to New Orleans."
"Descriptions, plane coordinates, and elevations of stations established by local control survey projects of the CWA and FERA in Michigan, 1933-1935."

The National Bureau of Standards has continued to cooperate with us by standardizing base-measurement tapes and by graduating circles for first- and second-order Parkhurst theodolites.

The latitude-observatories at Ukiah, California, and Gaithersburg, Maryland, have continued in operation throughout the year. These two observatories on the 39th parallel of latitude are part of the cooperative program in conjunction with the governments of Japan, Italy, and the Soviet Union for studies of the variation of latitude.

The Congress of the United States has provided an appropriation of $450,000 for the next fiscal year, an increase of $370,000 above that for the current year. It is our hope that this

or larger amounts will be provided in future years so that the program of horizontal and vertical control-surveys may continue on an intelligent and economical plan.

U. S. Coast and Geodetic Survey,
Washington, D. C.

NOTE ON TIDES IN WELLS

C. L. Pekeris

In his report on Earth tides read at the 1939 Congress of the International Union of Geodesy and Geophysics, Mr. Lambert described four cases of observed tides in wells which are situated far enough inland to be unaffected by the tidal load of the coastal waters. Mr. Lambert suggests that these tides are the direct effect of the tide-producing forces and are a manifestation of Earth tides. Evidence for this conclusion he sees in some of the features which are suggested by the available observations, namely, the relatively large ratio of the solar semidiurnal to the lunar semidiurnal components, the marked diurnal inequality, etc.

In all the wells one finds the remarkable phenomenon that for semidiurnal tides the lowest level of the water occurs at the time of the Sun's and Moon's transit.

It seems that such a phase-relationship would be expected if, as suggested by Lambert, the tides in the wells result from the compression and dilatation in the water-bearing strata due to Earth tides. Since the apparent tidal forces of the Moon pull outwards the portions of the Earth that are facing the Moon and those which are at its antipode and tend to push inwards the intermediate regions, it is clear that at the time of the Moon's transit, when the Earth tide is high, the region underneath the station is under tension and is dilated, while six hours later, when the Earth-tidal displacement is downwards, it is under compression.

Compression in the water-bearing region would squeeze the water into the well and would thus bring about a rise of the water-level at a time when the displacement due to the Earth tide is downwards. In order to verify the above inference and also to determine the order of magnitude of the dilatation which is associated with the Earth tides, I have used the solutions of the tidal problem given by Hoskins [see 1 of "References" at end of paper] and Stoneley [2], in which compressibility was allowed for.

Stoneley computes the bodily tide in a gravitating sphere in which, according to Wiechert's hypothesis, the density has the constant value of 8.21 in a core extending from the center to 0.78 of the radius, and the constant value of 3.12 in the remaining outer shell. In the core, the values $\mu = 38.2 \times 10^{11}$, $(\lambda + 2\mu) = 134.7 \times 10^{11}$ are adopted, while for the shell these constants are assumed to be given by

$$\mu = (50.78 - 45.71\,\xi) \times 10^{11}$$

$$\lambda + 2\mu = (164.0 - 147.5\,\xi) \times 10^{11} \text{ dynes/cm}^2$$

where ξ denotes the distance from the center in units of the Earth's radius.

The perturbing potential is of the form $\epsilon r^2 P_2(\cos\theta)$ and is denoted by W_2. One finds for the radial displacement u and the dilatation Δ the expressions

$$u = (1/r)(2F + r^2 G)W_2$$

$$\Delta = [(2/r)(dF/dr) + r(dG/dr) + 5G]W_2$$

where F and G are functions of r for which Stoneley assumes the following form

$$F(r) = A_0(r^2/a^2) + A_1(r^2/a^2)[(a - r)/a] + A_2(r^2/a^2)[(a - r)/a]^2 \ldots\ldots$$

$$G(r) = (B_0/a^2) + (B_1/a^2)[(a - r)/a] + (B_2/a^2)[(a - r)/a]^2 \ldots\ldots$$

From these expressions it follows that at the surface, where r = a,

$$u(a) = [W_2(a)/a]\,(2A_0 + B_0)$$

$$\Delta(a) = [W_2(a)/a\,]\,(4A_0 - 2A_1 - B_1 + 5B_0)$$

Stoneley gives the following values for the coefficients: $A_0 = -0.02149$; $A_1 = -0.4693$; $B_0 = -0.3834$; $B_1 = -0.6190$, in which the unit is 1/1000. Love's constants h and k for this model are found to be 0.37 and 0.19, comparing favorably with the observed values of 0.38 and 0.22.

It follows that

$$u(a) = -0.4264\ [W_2(a)/a]$$

$$\Delta(a) = -0.4453\ [W_2(a)/a^2]$$

or that

$$\Delta(a) = 1.04\ [u(a)/a]$$

Now, since in the assumed model the mean density is constant near the surface, the change in density $\delta\rho$ associated with the tidal motion is given by

$$-(\delta\rho/\rho) = \Delta = (\delta V/V)$$

where V is the specific volume.

Hoskins solves the tidal problem for a sphere of constant density and elasticity as well as for models in which the density and elastic constants increase with depth. For our purpose it will be sufficient to compute the dilatation for the case of constant density and elasticity. The physical constants enter this problem only through the combinations (λ/μ) and $b = g\rho a/\mu$. As usual, (λ/μ) is assumed to be unity and b was taken to be equal to 2.

With this value of b, h comes out 0.47, as against the observed value of 0.38, but this discrepancy is not serious for our application. Hoskins denotes the disturbing potential by $(cgr^2S_2/2a)$, where $S_2 = [\cos^2\theta - (1/3)]$, and $[u(a)/a]$ and $\Delta(a)$ by e_1S_2 and γS_2. In terms of the coefficients A_n, C_n, D_n that enter his solution

$$e_1 = \Sigma_0^\infty A_n,\quad \gamma = \Sigma_2^\infty C_n$$

To obtain these coefficients, one first determines the C_n and D_n in terms of C_2 and D_2 by Hoskins' equation (121), where n is taken to be zero. From the equations (120) and (122) one then finds that $D_2 = -1.783\ C_2$, $A_0 = 1.689\ C_2$, $C_2 = 0.2090c$. It follows that $\gamma = 0.0758c$ and, by equation (139), that $e_1 = 0.2345c$. The latter value checks the value of 0.235c given in Table 2 (p. 38). Hence

$$\Delta(a) = 0.323\ [u(a)/a] \qquad (2)$$

It is seen from (1) and (2) that the dilatation has the same sign as the radial displacement and that it is of the order of magnitude of the ratio of the tidal displacement to the radius of the Earth. For the lunar semidiurnal tide this amounts to about 1.5×10^{-8}. A change of level of one cm in a well of one-meter radius could be brought about by the above dilatation in a water-bearing hemisphere of only 100 meters in radius.

The preceding discussion suggests the possibility of observing Earth tides with a dilatometer. A cavity of 10^6 cc filled with a liquid and sealed by a capillary would undergo volume-changes of the order of ten cubic millimeters, which could be observed in the capillary. Disturbing effects of temperature-fluctuations could be minimized by observing at some depth underground, as is usual in Earth-tide work. Plans are under consideration to construct a dilatometer on the above principle or some variation of it with a view to using it for tidal observations.

References

[1] L. M. Hoskins, Trans. Amer. Math. Soc., v. 21, p. 31, 1920.
[2] R. Stoneley, Mon. Notices R. Astr. Soc., Geophys. Supp., v. 1, p. 356, 1926.

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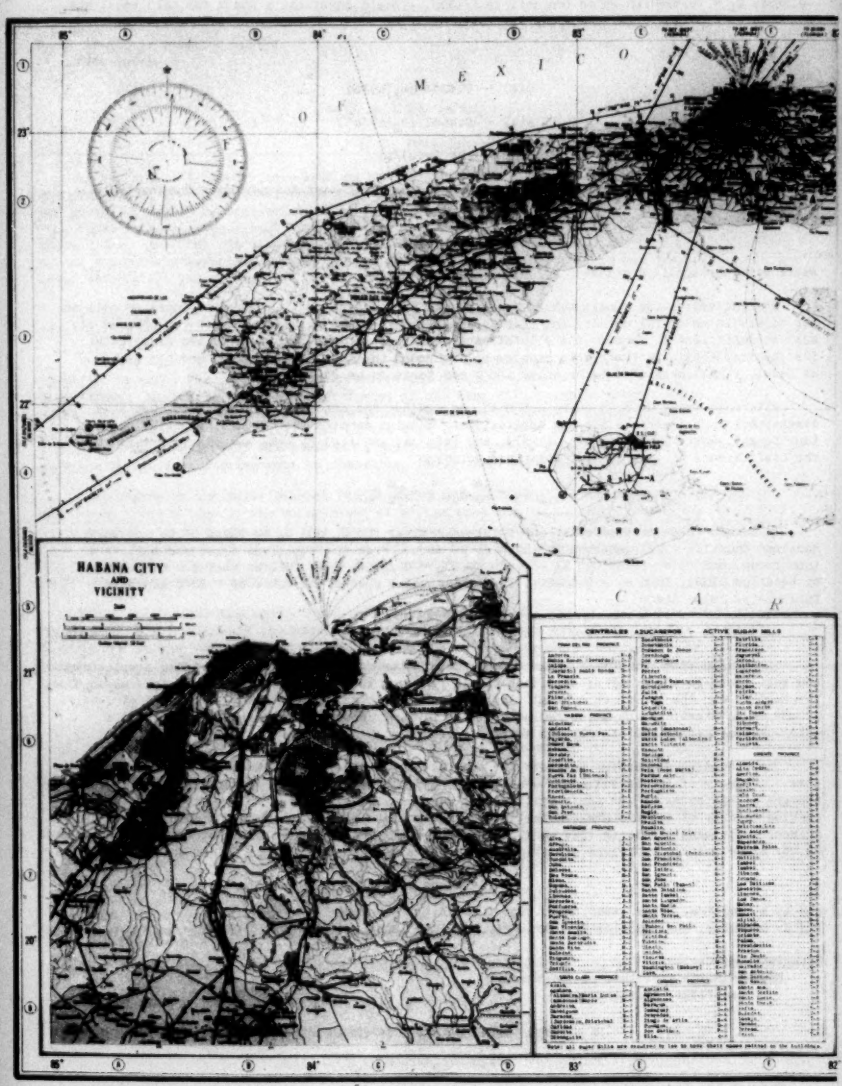
BASIC GRAVITY-SURVEY OF CUBA

Roy E. Dickerson

Through the cooperative efforts of the United States Coast and Geodetic Survey, the American Geophysical Union, and the Atlantic Refining Company of Cuba, 165 pendulum-stations with many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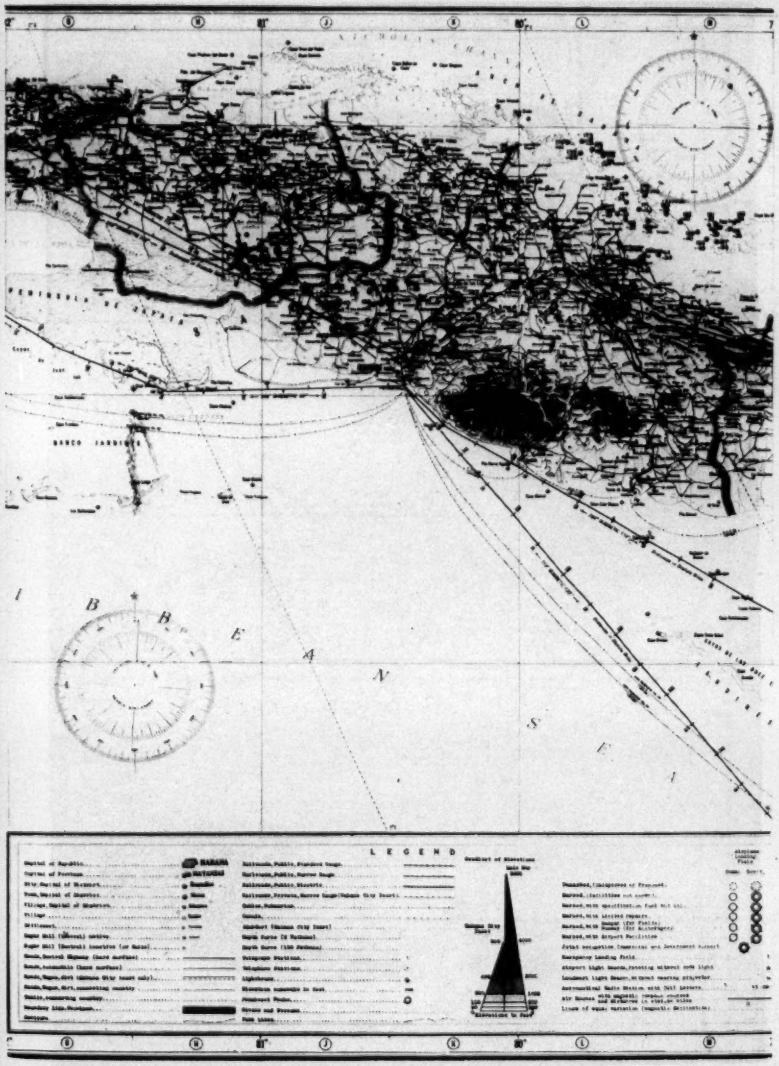
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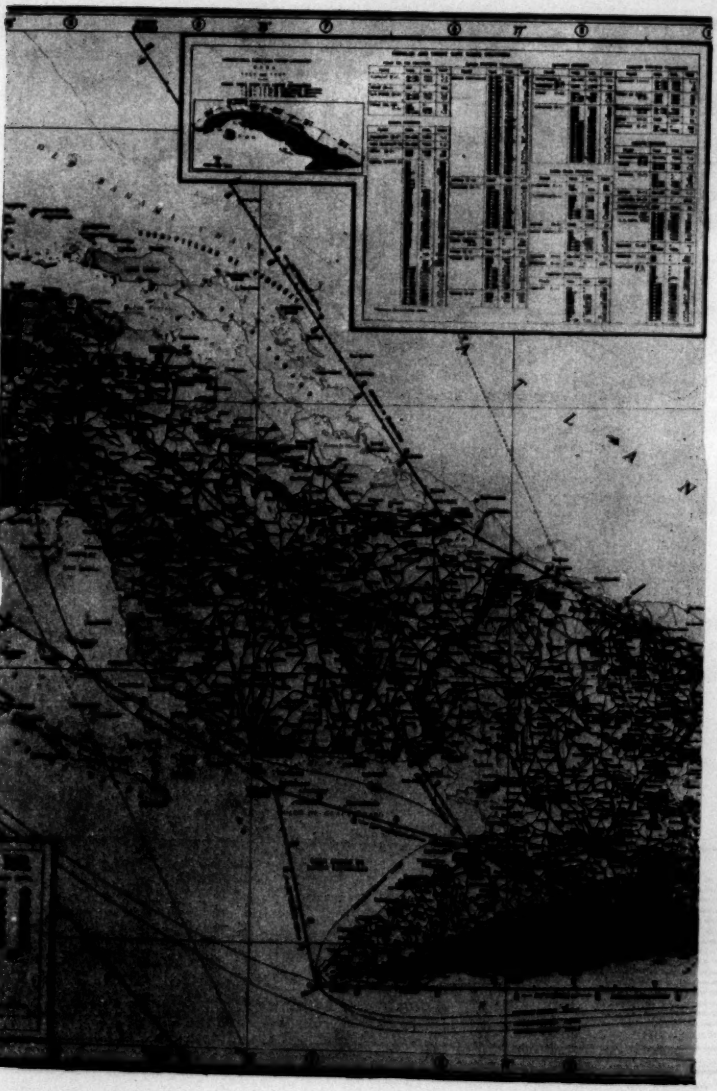

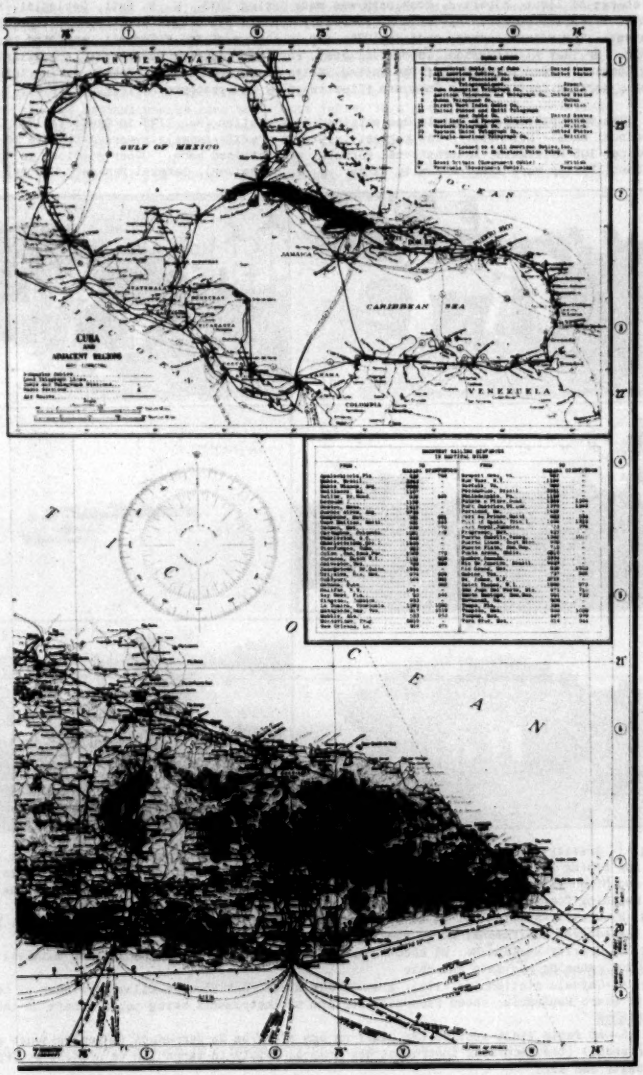
UNITED STATES
GULF OF MEXICO
ATLANTIC OCEAN
CARIBBEAN SEA
CUBA
AND
ADJACENT ISLANDS
JAMAICA
VENEZUELA
COLOMBIA
PANAMA
GUATEMALA
NICARAGUA
PACIFIC OCEAN

reoccupations of stations for checking have been executed in Cuba (see map). The first survey in charge of Lieut. Albert J. Hoskinson was made during 1933. W. H. Butt, Geologist, represented the Atlantic Refining Company. Harold McConnell was Lieut. Hoskinson's technical assistant. The second survey, made in 1935, was in charge of Mr. McConnell, assisted by Robert B. Wohld. Dr. Roy E. Dickerson, Chief Geologist, Foreign Producing Department, the Atlantic Refining Company, aided the staff of the United States Coast and Geodetic Survey during their stay in Cuba. Working conditions in Cuba are illustrated by the photographs (Figs. 1 to 6).

The most spectacular result was obtained at a station (No. 114) in Cauto Valley, Oriente Province, Cuba--"Dos Rios." The highest isostatic gravity-anomaly recorded to date in North America, 105 milligals, International Formula, was obtained here. Other stations in the center of Cauto Valley were also unusually large. V. J. Gianelloni, General Manager, Central San German,

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

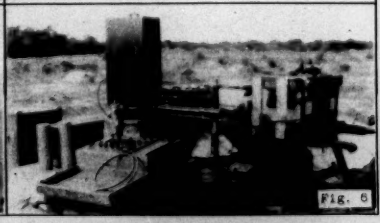
Fig. 6

Fig. 1--Gravity-equipment at Baracoa station (No. 78) just after receiving final (4 p.m.) signal for timing the pendulums [left to right: Isaac Corral, Director of Bureau of Forests, Waters, and Mines of the Cuban Department of Agriculture; William H. Butt, Geologist of the Atlantic Refining Company, and H. E. McConnell of United States Coast and Geodetic Survey]

Fig. 2--Gravity-station No. 14 at Guanabana Cemetery [instrument just set up and tent being placed over instrument; A. J. Hoskinson in action (right)]

Fig. 3--Gravity-station No. 68 about 2-1/2 kilometers northeast of Sabanilla, Matanzas Province, Cuba, showing portable antennae

Fig. 4--Cayuelo station (No. 172), a small limestone rock about 4 kilometers east of north end of Uvero Peninsula; shows recording portion of instruments being poled ashore in the Joven Gladys

Fig. 5--At Pablo Viejo station (No. 157) on one of Cayos de Herradura (a series south of Cayo Frances) [the recording instrument was wrapped doubly in tarpaulin to protect it from the salty sea air]

Fig. 6--Instruments inside the "caja del muerto" at Pablo Viejo

collected a sample of basaltic rock from a locality about ten kilometers (six miles) east of this station. The station is on alluvium of the Cauto River Valley. Miocene limestone outcrops about 15 kilometers (nine miles) north of the station at Central San German. Oligocene limestone with north dip was found about six kilometers (3.5 miles) south of the station. The occurrence of basaltic rock east of Dos Rios (near the confluence of the rivers, Cauto and Contramaestre) suggests that an ultrabasic igneous mass lightly mantled by Recent Alluvium is the cause of these very high value anomalies in the center of Cauto Valley. Obviously this explanation is in opposition to the old reconnaissance idea that Cauto Valley is a great syncline. Detailed geologic mapping in Cauto Valley has not yet been executed but this preliminary geophysical work will help greatly in solving the structural problems of this feature.

The following rock-types of the Earth's crust are set forth by A. C. Lawson [Insular arcs,

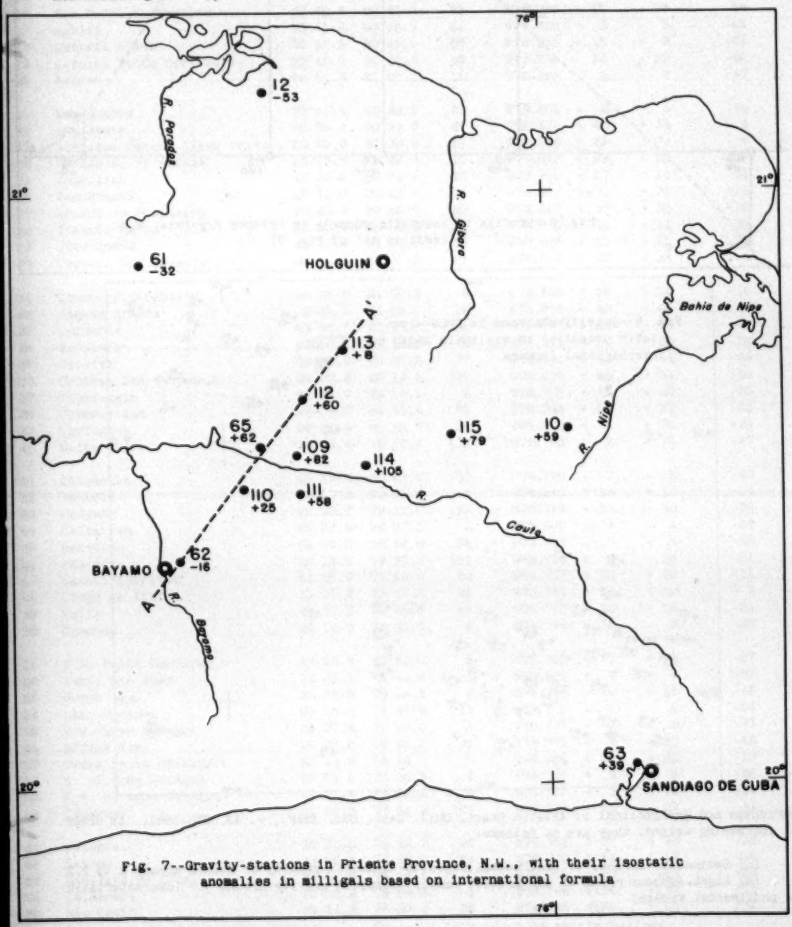

Fig. 7--Gravity-stations in Priente Province, N.W., with their isostatic anomalies in milligals based on international formula

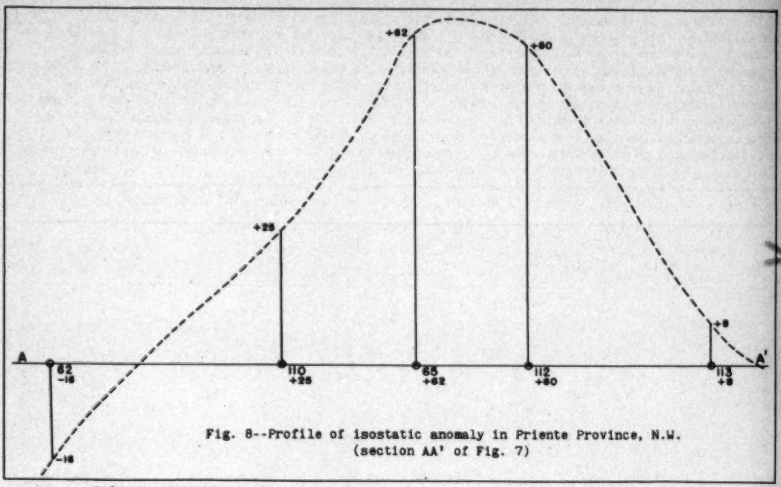

Fig. 8--Profile of isostatic anomaly in Priente Province, N.W. (section AA' of Fig. 7)

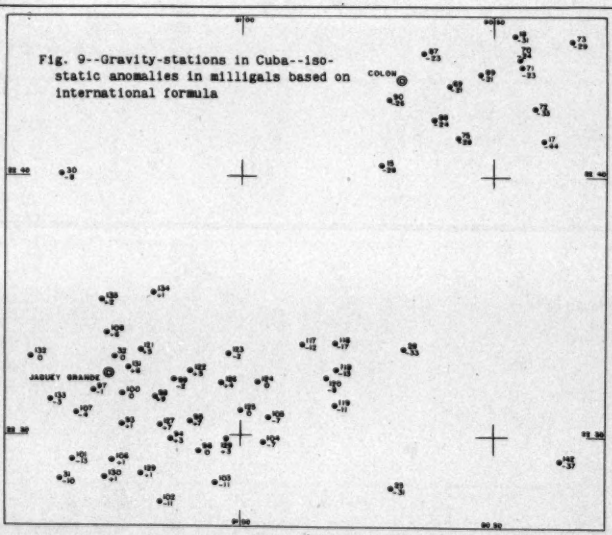

Fig. 9--Gravity-stations in Cuba--isostatic anomalies in milligals based on international formula

foredeeps and geosynclinal of Asiatic Coast, Bull. Geol. Soc. Amer., v. 43, 353-386]. In order of increasing weight, they are as follows:

(1) Sediments, marine, or continental deposits--specific gravity of strata around 2 to 2.2
(2) Light igneous rocks of the granite family--specific gravity around 2.7 (characteristic of continental masses)

Table 1--Gravity-stations in Cuba

No.[a]	Name of station	Latitude	Longitude	Elevation	Observed gravity	Anomaly		
						Free air	Bouguer	Isostatic (113.7)
		° '	° '	meters	gals	mgals	mgals	mgals
10	Alto Cedro	20 35.9	75 57.6	76	978.789	+125	+117	+59
11	Cayo Mambi	20 40.6	75 16.3	15	978.825	+139	+139	+67
12	Chaparra	21 10.1	76 29.3	13	978.726	+ 9	+ 9	-53
13	Habana	23 08.5	82 22.4	38	978.850	+ 17	+ 17	-42
14	Guanabana	22 59.3	81 30.8	71	[b]978.830	+ 17	+ 9	-37
15	Guareiras	22 40.4	80 54.5	37	[b]978.822	+ 18	+ 14	-28
16	San Pedro de Mayaban	22 42.5	80 35.0	67	978.786	- 10	- 18	-56
17	Aguica	22 41.4	80 48.0	54	978.802	+ 3	- 3	-44
18	Central Alava	22 45.5	80 49.2	56	978.818	+ 15	+ 9	-31
19	Central Santa Gertrudis	22 49.5	80 50.9	39	978.794	- 18	- 22	-62
20	Recreo	22 54.6	81 00.5	16	978.820	- 5	- 6	-47
21	Los Arabos	22 45.8	80 42.5	65	978.802	+ 2	- 5	-44
22	Angostura	22 35.4	80 29.6	69	978.834	+ 46	+ 38	- 1
23	Santiago (Santa Clara Prov.)	22 30.9	80 30.4	67	978.826	+ 42	+ 34	- 6
24	Km 246 E. of Havana	22 37.8	80 22.4	72	978.819	+ 29	+ 21	-17
25	Amarillas	22 28.0	80 54.0	20	978.812	+ 17	+ 15	-31
26	Yaguaramas	22 15.6	80 42.4	25	978.853	+ 73	+ 71	+19
27	Aguada de Pasajeros	22 23.2	80 50.9	20	978.827	+ 37	+ 35	-12
28	Central Maria	22 33.4	80 53.5	29	978.812	+ 14	+ 11	-33
29	Jovellanos	22 47.4	81 11.3	28	978.828	+ 15	+ 12	-30
30	Central San Ignacio	22 40.1	81 07.2	27	978.843	+ 37	+ 34	- 8
31	Chucho Algoroba	22 28.3	81 07.2	8	978.836	+ 36	+ 36	-10
32	Jaguey Grande	22 33.1	81 05.0	12	978.846	+ 43	+ 43	0
33	Cardenas	23 00.7	81 10.4	2	978.797	- 38	- 38	-82
34	Varadero	23 09.0	81 15.9	5	978.815	- 28	- 28	-76
35	Jicotea	22 30.2	80 07.2	77	978.802	+ 22	+ 14	-24
36	Central Dos Hermanos	22 22.2	80 14.8	108	978.805	+ 43	+ 31	-10
37	Cienfuegos	22 07.9	80 26.8	2	978.798	+ 19	+ 20	-35
38	Cumanayagua	22 09.9	80 14.6	60	978.796	+ 33	+ 27	-22
39	Cartagena	22 24.8	80 25.7	37	978.861	+ 74	+ 70	+28
40	Santa Clara	22 25.4	79 59.4	112	978.786	+ 2	- 10	-47
41	Cifuentes	22 37.8	80 03.6	56	978.788	- 7	- 13	-49
42	Isabela	22 55.2	80 02.0	0	978.844	+ 13	+ 13	-24
43	Zulueta	22 22.7	79 34.0	199	978.720	- 15	- 35	-69
44	Caibarien	22 31.5	79 27.2	2	978.800	- 4	- 4	-38
45	Remedios	22 29.5	79 33.4	28	978.788	- 6	- 9	-43
46	Placetas	22 18.8	79 39.6	191	978.735	+ 2	- 18	-51
47	Sancti Spiritus	21 55.9	79 26.6	52	978.787	+ 35	+ 30	-11
48	Ciego de Avila	21 51.7	78 47.5	45	978.784	+ 35	+ 29	- 9
49	Falla	22 10.3	78 45.9	15	978.763	- 15	- 16	-51
50	Chambas	22 19.8	78 52.0	6	978.789	- 2	- 3	-36
51	S.W.-Punta San Juan	22 22.8	78 53.0	5	978.801	+ 7	+ 7	-27
52	Punta San Juan	22 22.1	78 46.4	5	978.800	+ 7	+ 6	-27
53	Moron	22 08.2	78 36.8	4	978.768	- 12	- 12	-46
54	Loma Cunagua	22 06.8	78 27.9	11	978.775	- 1	- 2	-36
55	N.W.-Loma Cunagua	22 07.6	78 29.2	4	978.777	- 2	- 2	-37
56	Arroyo Yeso	22 05.8	78 25.5	30	978.762	- 7	- 10	-43
57	Playa Santa Gertrudis	22 10.6	78 18.1	0	978.805	+ 22	+ 22	-13
58	S. of Loma Cunagua	22 02.8	78 25.3	4	978.776	+ 2	+ 2	-32
59	N.E. of Loma Cunagua	22 07.4	78 24.2	8	978.775	- 3	- 3	-38
60	Camaguey	21 24.2	77 54.2	100	978.694	- 10	- 21	-62
61	Oriente	20 53.0	76 42.7	95	978.708	+ 33	+ 23	-32
62	Bayamo	20 22.8	76 38.7	54	978.708	+ 51	+ 47	-16
63	Santiago de Cuba	20 01.6	75 51.1	7	978.778	+127	+133	+39
64	Caimanera	19 58.8	75 09.5	1	978.756	+105	+112	+15
65	Rio Cauto	20 34.3	76 30.1	38	978.796	+123	+120	+62

[a]Nos. 1 to 9 are on other islands. [b]Mean of 1933 and 1935 determinations.

Table 1--Gravity-stations in Cuba--Continued

No.	Name of station	Latitude	Longitude	Elevation	Observed gravity	Anomaly		
						Free air	Bouguer	Isostatic (113.7)
		° ′	° ′	meters	gals	mgals	mgals	mgals
66	Central Moron	22 01.8	78 40.9	38	978.744	+ 18	- 22	-58
67	Union de Reyes	22 47.3	81 28.4	68	978.892	+ 91	+ 83	+41
68	Sabanilla	22 53.1	81 31.1	109	978.858	+ 64	+ 52	+ 8
69	2 1/2 km N.E.-Colon	22 43.5	80 51.8	48	978.828	+ 25	+ 19	-21
70	5 km S. 18° E.-Banaguises	22 44.6	80 49.1	57	978.823	+ 22	+ 15	-24
71	5.6 km S.E.-Banaguises	22 44.3	80 48.9	54	978.825	+ 23	+ 17	-23
72	400 M. N. of km 199	22 42.7	80 48.4	62	978.812	+ 14	+ 7	-33
73	4.2 km N. 25° W. of K 204	22 45.3	80 46.8	58	978.818	+ 16	+ 9	-29
74	5 km S.-Mordazo	22 36.5	80 26.2	71	978.828	+ 39	+ 31	- 7
75	5 km S. 45° E. of Colon	22 41.5	80 51.4	38	978.822	+ 18	+ 13	-28
76	Bacuranao	23 09.4	82 11.3	17	978.860	+ 19	+ 20	-37
77	Bauta	23 00.3	82 33.4	56	978.862	+ 43	+ 38	-19
78	Baracoa	23 02.8	82 33.5	11	978.849	+ 13	+ 14	-47
79	Guanimar	22 41.4	82 39.3	1	978.850	+ 34	+ 34	-18
80	Artemisa	22 48.8	82 46.5	41	978.836	+ 25	+ 21	-35
81	Pinar del Rio	22 26.2	83 41.5	57	978.795	+ 13	+ 8	-59
82	La Coloma	22 14.9	83 34.6	1	978.857	+ 69	+ 70	- 1
83	San Cayetano	22 43.6	83 45.2	33	978.872	+ 64	+ 62	-11
84	Taco Taco	22 40.3	83 09.	50	978.821	+ 21	+ 15	-40
85	Batabano	22 42.5	82 17.8	2	978.873	+ 57	+ 57	+ 7
86	Matanzas	23 03.0	81 34.2	1	978.830	- 9	- 9	-57
87	2 1/2 km N. of Colon	22 44.8	80 52.8	58	978.825	+ 24	+ 17	-23
88	2 1/2 km S. 45° E.-Colon	22 42.2	80 52.4	38	978.825	+ 20	+ 16	-24
89	5 km N. 80° E.-Colon	22 44.0	80 50.6	63	978.826	+ 26	+ 19	-21
90	1 1/2 km S.W.-Colon	22 43.0	80 54.2	37	978.825	+ 19	+ 15	-26
91	W. Ent. Pt. Matanzas Bay	23 05.3	81 31.5	6	978.824	- 15	- 15	-63
92	Boca Cañimar	23 03.0	81 30.1	2	978.829	- 9	- 9	-56
93	Quemado Road	22 30.5	81 04.7	10	978.849	+ 48	+ 47	+ 1
94	Quemado Grande	22 29.9	81 02.8	10	978.849	+ 49	+ 48	+ 3
95	Finca San Rafael	22 30.6	81 02.0	13	978.853	+ 53	+ 52	+ 7
96	Los Guaos	22 29.4	81 01.7	12	978.846	+ 47	+ 46	0
97	Jaguey Grande	22 31.8	81 05.8	9	978.847	+ 44	+ 43	- 1
98	Batey Dueñas	22 31.6	81 03.4	15	978.856	+ 56	+ 55	+ 9
99	Colegio Rubira	22 32.2	81 02.7	16	978.846	+ 45	+ 44	- 2
100	Casa Izquierda	22 31.7	81 04.7	12	978.847	+ 46	+ 45	0
101	South of Central Australia	22 29.1	81 06.7	6	978.834	+ 33	+ 33	-13
102	Murga	22 27.5	81 03.2	8	978.834	+ 35	+ 35	-11
103	Juanita	22 28.2	81 01.0	7	978.836	+ 36	+ 36	-11
104	Viajaca	22 29.8	80 59.1	10	978.839	+ 39	+ 38	- 7
105	North of Viajacas	22 30.7	80 58.9	15	978.839	+ 40	+ 39	- 7
106	Rosario	22 29.1	81 05.1	10	978.847	+ 47	+ 46	+ 1
107	Emilia B	22 30.9	81 06.5	9	978.844	+ 42	+ 42	- 4
108	Gallo	22 34.0	81 05.3	14	978.854	+ 50	+ 49	+ 6
109	Ingenio Viejo	20 33.7	76 26.5	58	978.814	+147	+142	+82
110	Babiney	20 30.0	76 31.9	62	978.753	+ 91	+ 86	+25
111	Finca Seca	20 29.7	76 26.3	52	978.789	+124	+119	+58
112	Finca Ramirez	20 39.2	76 25.8	52	978.797	+123	+118	+60
113	Cacocum	20 44.0	76 21.3	71	978.745	+ 72	+ 65	+ 8
114	Dos Rios	20 32.2	76 19.3	69	978.834	+172	+165	+105
115	San German	20 35.6	76 10.1	85	978.807	+147	+139	+79
116	Finca La Quinta	22 33.7	80 56.3	17	978.831	+ 28	+ 27	-17
117	Santa Irene	22 33.6	80 57.6	22	978.834	+ 34	+ 32	-12
118	Esquina	22 32.6	80 56.2	21	978.833	+ 33	+ 31	-13
119	Isabel	22 31.2	80 56.2	15	978.834	+ 34	+ 33	-11
120	Callejon Viuda	22 32.3	80 56.6	18	978.837	+ 37	+ 36	- 8

Table 1--Gravity-stations in Cuba--Concluded

No.	Name of station	Latitude	Longitude	Elevation	Observed gravity	Anomaly		
						Free air	Bouguer	Isostatic (113.7)
		° '	° '	meters	gals	mgals	mgals	mgals
121	Finca Esperanza	22 33.3	81 04.0	19	978.851	+ 50	+ 48	+ 5
122	Callejon Horcado	22 32.6	81 02.0	25	978.850	+ 52	+ 49	+ 5
123	Prendes	22 33.2	81 00.5	28	978.843	+ 45	+ 42	- 2
124	South of Pasquala	22 32.1	80 59.3	26	978.845	+ 47	+ 44	0
125	Finca Los Billares	22 31.0	81 00.0	18	978.844	+ 45	+ 43	0
126	Ultima Parada	22 32.1	81 00.8	23	978.849	+ 50	+ 48	+ 4
127	Finca Timotea	22 30.5	81 03.2	17	978.852	+ 53	+ 51	+ 7
128	Guaos Road	22 29.9	81 00.6	14	978.848	+ 49	+ 48	+ 3
129	Batey Diaz	22 28.6	81 04.0	10	978.846	+ 47	+ 46	+ 1
130	Finca Perez	22 28.4	81 05.4	7	978.847	+ 47	+ 47	+ 1
131	Hernandez	22 32.7	81 04.6	20	978.852	+ 52	+ 50	+ 6
132	Kilometer 30	22 31.1	81 08.4	10	978.848	+ 44	+ 43	0
133	Camino Lopez	22 31.4	81 07.6	7	978.845	+ 43	+ 42	- 3
134	Finca Santa Teresa	22 35.6	81 03.6	26	978.849	+ 47	+ 44	+ 1
135	Finca Santo Domingo	22 35.3	81 05.5	16	978.850	+ 46	+ 45	+ 2
136	Real Campiña	22 19.5	80 45.0	27	978.845	+ 61	+ 59	+ 9
137	Central Covadonga	22 16.0	80 50.7	7	978.857	+ 70	+ 70	+18
138	Finca San Andres	22 19.2	80 51.0	11	978.849	+ 60	+ 59	+ 9
139	Carreños	22 21.2	80 47.3	33	978.838	+ 54	+ 51	+ 2
140	Finca Asturias	22 20.8	80 43.0	45	978.837	+ 57	+ 53	+ 4
141	Galeon	22 22.5	80 53.6	12	978.834	+ 42	+ 41	- 7
142	Finca La Gloria	22 29.1	80 47.3	26	978.805	+ 10	+ 8	-37
143	Esles	22 24.7	80 42.4	56	978.827	+ 46	+ 40	- 6
144	Central Cienegita	22 16.4	80 35.5	39	978.846	+ 69	+ 66	+16
145	Violeta	22 24.7	80 46.5	42	978.823	+ 38	+ 34	-14
146	Jabacoa	22 22.8	80 35.0	26	978.844	+ 56	+ 53	+ 8
147	Enlace Capitan	22 23.3	80 38.6	49	978.826	+ 44	+ 39	- 7
148	Palma Sola	22 26.0	80 37.4	48	978.817	+ 33	+ 28	-16
149	Balbin	22 23.3	80 31.6	24	978.864	+ 74	+ 72	+26
150	Santa Elena	22 20.0	80 34.5	41	978.843	+ 63	+ 59	+12
151	Rodas	22 20.8	80 31.8	16	978.847	+ 58	+ 57	+10
152	Jaguey Cnico	22 25.7	80 52.7	18	978.824	+ 31	+ 30	-17
153	La Guinea	22 33.6	80 40.9	55	978.774	- 16	- 22	-64
154	James	22 28.3	80 40.7	45	978.803	+ 15	+ 10	-34
155	Cayo Borracho	22 39.2	79 09.1	1	978.813	0	0	-36
156	Farallon La Arena	22 37.7	79 10.3	1	978.814	+ 2	+ 2	-35
157	Pueblo Viejo	22 34.5	79 13.3	2	978.805	- 2	- 2	-38
158	Cayo Cobos	22 35.1	79 15.7	1	978.805	- 4	- 4	-40
159	Cayo Boca Chica	22 36.8	79 17.9	1	978.807	- 4	- 4	-40
160	Piedra Blanca	22 37.8	79 12.6	7	978.816	+ 6	+ 6	-30
161	Cayo Frances	22 38.6	79 13.7	2	978.817	+ 5	+ 5	-32
162	Cayo Fragoso	22 38.8	79 22.3	1	978.809	- 4	- 4	-40
163	Cayo Oye Ortiz	22 40.5	79 25.6	1	978.816	+ 1	+ 1	-35
164	Virazon	22 39.1	79 29.6	0	978.814	+ 1	+ 1	-35
165	Punta Guasi	22 39.2	79 35.1	1	978.818	+ 5	+ 5	-32
166	Laguna del Medio	22 40.6	79 37.1	1	978.819	+ 4	+ 4	-33
167	Guaquelli	22 47.7	79 37.6	1	978.831	+ 9	+ 9	-29
168	El Santo	22 42.1	79 40.8	5	978.819	+ 5	+ 5	-33
169	Cayo Sombrero	22 43.1	79 34.8	1	978.829	+ 11	+ 11	-26
170	Boca Anton	22 44.5	79 30.2	1	978.822	+ 3	+ 3	-34
171	Cayo El Indio	22 41.5	79 31.8	1	978.820	+ 4	+ 4	-32
172	Cayuelo	22 54.1	79 45.8	1	978.846	+ 17	+ 17	-22
173	Punta Tocinera	22 54.9	79 43.2	1	978.854	+ 24	+ 24	-15
174	Cayo Dutton	22 53.5	79 40.6	1	978.843	+ 14	+ 14	-25
175	Cayo La Vela	22 56.7	79 45.3	1	978.859	+ 27	+ 28	-12
176	Cayo Lanzanillo	22 56.5	79 48.3	0	978.861	+ 29	+ 29	-11
	Means with regard to sign					+ 33	+ 30	-15
	Means without regard to sign					36	35	26

(3) Heavy igneous rocks of the basalt family (or heavy metamorphics)--specific gravity around 3.0

(4) Still heavier igneous rocks of the peridotite (dunite) family--specific gravity around 3.5

Obviously, gradations of specific gravity within this somewhat arbitrary grouping may be recognized. The San Cayetano formation of Jurassic age and its associated igneous rocks correspond approximately to Group 2, or between Group 2 and Group 3. With these specific gravities in mind, note that Station No. 38, Cumanayagua, is on a granitoid rock, with a value of -22. Other granitoid stations at Sancti Spiritus (No. 47) and Ciego de Avila (No. 48) indicate that "granite" values lie between -9 and -22.

Two stations were placed in areas of serpentine rocks. Bacuranao, Havana Province, Station No. 76, had an anomaly of -37. At this place, the serpentine is probably a laccolitic sill intruded in Upper Cretaceous shale and sandstone. The other station, Santa Clara (No. 40), was about two kilometers west of Santa Clara City in Santa Clara Province. Its anomaly was -47. Neither station was notably high or low. The theory that serpentine becomes a dense ultrabasic in depth receives no support from these results. The large anomaly of +26 at Turquino (Balbin No. 149), southern Santa Clara Province, probably is due to ultrabasic rock since a dense basalt outcrops nearby. The Union de Reyes station (No. 67) in southern Matanzas Province (+41) indicates a dense igneous dike lightly mantled by Quaternary and Upper Tertiary limestones. There are other large anomalies which very probably are due to dense igneous rock now mantled by Quaternary and Tertiary limestones.

[Note: This paper was communicated through the Section of Geodesy and was not one of the papers delivered at the twenty-first annual meeting.]

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Philadelphia, Pennsylvania

PROGRESS OF GEODETIC WORK IN MEXICO DURING THE YEAR 1939

Manuel Medina

No manuscript or abstract was submitted for this paper.

Dirección de Geografía, Meteorología e Hidrología,
Tacubaya, D. F., Mexico

AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF SEISMOLOGY

REPORTS AND PAPERS

Washington, D.C.
April 25, 1940

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SEASONAL PRESSURE-CHANGES AND EARTHQUAKE-OCCURRENCE

H. Landsberg

The effects of the barometric pressure and its changes upon the occurrence of earthquakes have always found considerable interest on the part of seismologists. Direct influences upon the time of release of an earthquake have been suspected for single great earthquakes and are established in a statistical fashion for certain epicentral regions. Reference is made here only to the papers of Conrad [see 1 and 2 of "References" at end of paper], Nopcsa [3], Omori [4], Tams [5], and Hayes [6]. The gist of the findings has been summarized by Conrad [7] stating that the absolute value of the pressure in the epicentral region is of little or no influence but that the pressure-gradient and the tendency of the pressure have to be ranked among the trigger-forces responsible for the release of earthquakes.

An entirely different mode of pressure-influence upon earthquakes was visualized some years ago by the writer in connection with an investigation on the occurrence of deep-focus earthquakes [8]. It was found at that time that the deep-focus earthquakes in the interval 1918-29 showed an annual fluctuation with two peaks, one in spring and one in autumn. The suggestion was made that this was due to a trigger-effect of the motion of the Earth's pole. The pole-motion itself was attributed to changes in the moments of inertia of the Earth produced by mass-transports in the atmosphere. These mass-transports are a more or less regular occurrence due to the seasons. Air-masses are shifted across the equator in the spring of the Northern Hemisphere to the south and vice versa in the fall. The Asiatic Continent is a major contributor to these shifts of air-masses with its great high-pressure area in winter and low-pressure area in summer. Figure 1 shows the absolute values of the average annual pressure-changes over Asia. At the time when this hypothesis was advanced only 215 deep-focus earthquakes were available for investigation. In the meantime many more deep-focus shocks could be located. They have been critically reviewed and tabulated by Gutenberg and Richter [9]. From their catalogue 510 deep-focus earthquakes could be used for a revised annual distribution of these earthquakes. If obvious aftershocks are eliminated and adjustments are made for variable length of months by slight smoothing, the curve of Figure 2 results. In general, it still shows peaks in the spring and in autumn. Simultaneous with the writer's proposal to attribute these peaks to a pole-motion induced by pressure-variations on the Earth, V. Conrad in a periodogram-analysis came independently to the conclusion that both the deep-focus earthquake and the pole-motion periodograms contained cyclical elements of identical phase-length [10].

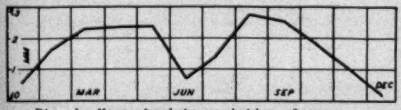

Fig. 1--Mean absolute variation of pressure over Asiatic Continent

For lack of further evidence the matter rested at this point for a while. Last December at the annual meeting of the American Meteorological Society, in Columbus, L. Page presented in connection with an entirely different matter, namely, investigations on atmospheric circulation of the United States Weather Bureau, a curve representing the pressure-variations on the Northern Hemisphere for the decade 1921-30. This work gave the opportunity to reopen the question of pressure-influence upon earthquakes. As the number of deep-focus shocks in any given month is too small to yield significant results, it was decided to use all heavy earthquakes, independent of focal depth, for the same decade. The earthquakes were taken from the International Seismological Summary. If the P-waves of a shock were recorded at distances greater than 80°, it was regarded as a "heavy earthquake." In this fashion even earthquakes in regions with no seismograph stations would be included. Inasmuch as the number of earthquakes listed in the Summary increased from year to year during the period in question, the percentage of earthquakes in each season in terms of total annual number was used. In tabulating these numbers it was immediately obvious that no fixed annual periodicity was prevalent in the material. The season with the maximum percentage shifted from year to year and every season had at least in one year during the decade the maximum number of shocks. The percentage varied between 17 and

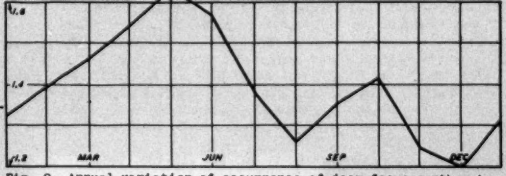

Fig. 2--Annual variation of occurrence of deep-focus earthquakes

37, with the mean being, of course, 25 per cent. These values were then compared to the seasonal transports of air taken from Dr. Page's graph, representing the total mass of air between the North Pole and 15° northern latitude. The result is graphically represented in Figure 3. Even a first glance shows that the trends of pressure on the Northern Hemisphere and the number of earthquakes correspond rather well. The correlation-coefficient between the two curves was calculated. It is $r = 0.56 \pm 0.075$. The coefficient is seven and one-half times greater than its probable error, which can be considered to be a statistically close correlation. The significance of this coefficient expressed in words would be that there existed during the decade 1921-30 a close relation between the air-mass transports across the equator and the number of earthquakes. Considering the many other influences upon earthquakes, this relation is very remarkable but it should be by no means implied that there is a direct and immediate influence of the air-mass transports, or pressure-changes, on earthquakes. It seems more reasonable to use this statistical result as a further argument in favor of the above-mentioned hypothesis that interposes the pole-motion between the air-mass transport and the earthquake-activity.

The somewhat complicated course of events may be summarized as follows:

Climatological and meteorological conditions, especially the change of seasons produce a transport of large masses of air from one hemisphere to the other. This process is subjected to the changes in the general atmospheric circulation. A change in mass-distribution on the Earth results in a change of position of the Earth's poles of rotation. Such a shift of the poles brings each region of the Earth under a different centrifugal force. If there are in any part of the Earth's crust or in the subcrustal material latent energies piled up to the verge of breaking, the small change in centrifugal force may act as trigger that releases them and sets off an earthquake.

The rather high correlation-coefficient found between earthquake-numbers and hemispherical

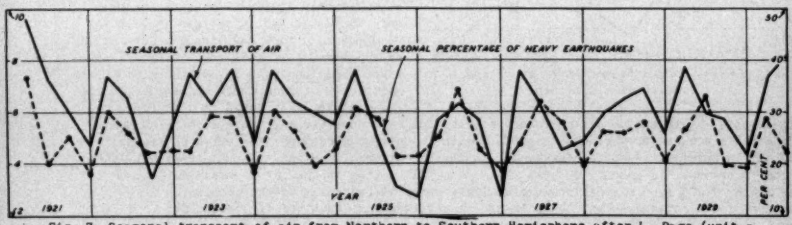

Fig. 3--Seasonal transport of air from Northern to Southern Hemisphere after L. Page (unit = 6.936×10^{17} grams) and seasonal percentage of heavy earthquakes in terms of total annual number, 1921-1930

pressure-changes places the latter ones in the class of a very important trigger-force, at least for the decade 1921-30. It remains to be seen if later intervals confirm the results. It would be very desirable in this connection if the pole-motion itself could be directly correlated to the pressure-changes on one side and the earthquakes on the other.

The writer is indebted to Dr. L. Page of the United States Weather Bureau for kindly furnishing the graph of pressure-changes on the Northern Hemishere referred to above.

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EARTHQUAKES IN THE WEST INDIAN REGION

Daniel Linehan

At the 1939 meeting of the Eastern Section of the Seismological Society of America, the author presented a paper on earthquakes occurring about 15° to 30° distance from Weston, Massachusetts. The difficulty of locating these quakes was stressed in the paper, due to the strange characteristics of the recordings. Observers of many stations thought of them as a series of "locals". Using the records from Williamstown, Harvard, Ottawa, and Fordham along with those of Weston, the author located these disturbances just north of the West Indies. He afterwards learned that one or two of them had been felt at Puerto Rico.

Earthquake-history of the area--Seismic activity in the West Indies has been well known

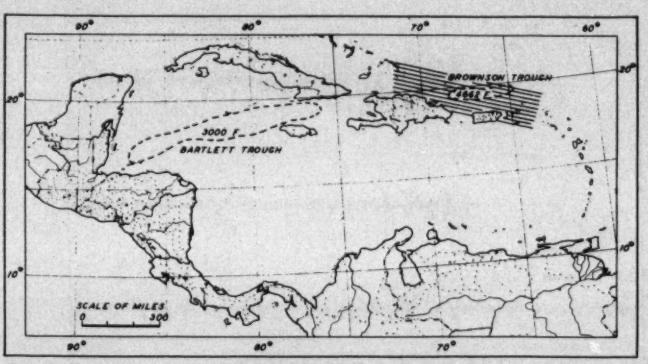

Fig. 1--West Indian Area; shaded portion shows area where majority of epicenters mentioned were located

even prior to any instrumental investigation. Even today many shocks are of sufficient strength to be felt. The number of shocks has not been large and does not compare with the number occurring in the East Indies. Our reason for making this comparison comes from the many apparent tectonic similarities existing in both places, especially the design of the negative gravity-anomaly arcs. A comparison of the seismic activity from 1918 to 1930 demonstrates that the major activity in the East Indies is about 12 times greater than in the West Indies, and we may imagine that minor activity would hold about the same proportion.

Importance of seismic studies in West Indies--Theories have been proposed concerning the tectonics producing the great gravity-arc that encircles the Caribbean Sea. It seems likely to many that mechanical motion of the crust must be involved, and if this is so we should expect seismic effects of this motion. The only sort of flow without seismic motion would be a liquid flow and this is most unlikely in the case of the Earth's crust. Some have stated there is no evidence of seismic motion from this area near the gravity-arc. We feel, however, that this lack of evidence has been due entirely to the inadequacy of the seismometers in use. As will be stated below, instruments of high sensitivity and short period (one second) are necessary.

Current seismic activity--For a three-year period, 1937 to 1939, we have instrumental evidence of about 50 quakes happening near the West Indies. Unfortunately, the station-records we have studied are all from New England and Canada, and as the azimuths of these stations from the region under study are about the same there is lack of good control over the arc-distance intersections. Even a preliminary examination, however, shows that the great majority are just slightly north of the gravity-arc and southeast of the Bahama Islands. None to date has been located east of the Lesser Antilles, although locations of the International Seismological Summary for the period from 1918 to 1930 place four out of the 12 West Indian quakes there, while only two have been located north of the arc. One recently located offered good control from the readings of the station at Kingston, Jamaica. This again was north of the gravity-arc. The hope of more accurate readings for the future is increased now that the station at Kingston has begun operation.

Characteristics of the seismograms--As has been mentioned, the records from this area are quite different from those we have recorded from other locations. The predominant characteristic is the multiplicity of phases and their extremely short period. The Earth-period recorded at New England from these quakes is rarely more than one second, which seems a little odd for quakes of this distance. If we keep the same distance and change the azimuth for quakes from Mexico, the record takes on a more normal appearance. Whether this difference is due to the mechanics at the source, the geological location of the focus, or the wave-path followed, we can not say.

The so-called P-group may last as long as three or four minutes due to the multiplicity mentioned and frequently runs into the S-group. The second group lasts about the same length of time as the former. About 20 minutes after the P-group is a third unidentified group which we have labelled as T. These are definitely transverse in character and also short-period. In the

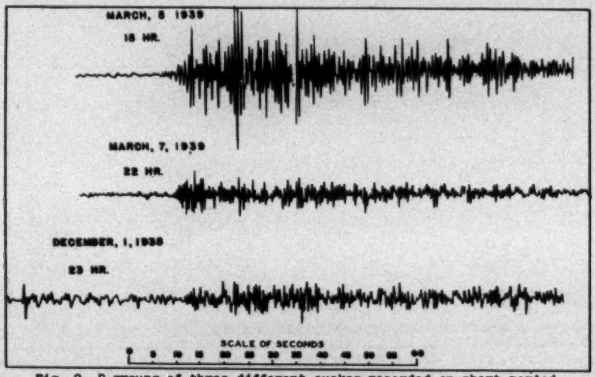

Fig. 2--P-groups of three different quakes recorded on short-period Benioffs at Weston

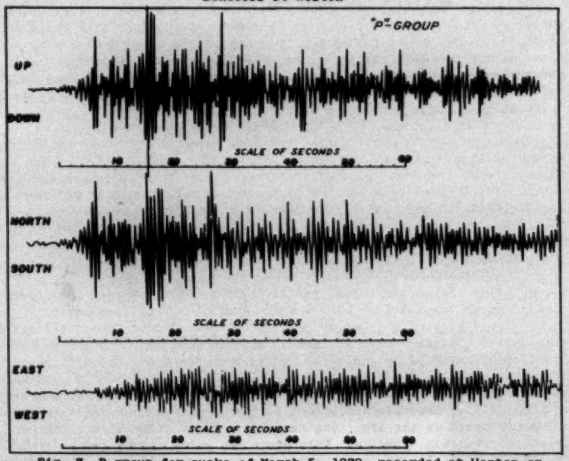

Fig. 3--P-group for quake of March 5, 1939, recorded at Weston on short-period Benioffs at 15^{n}

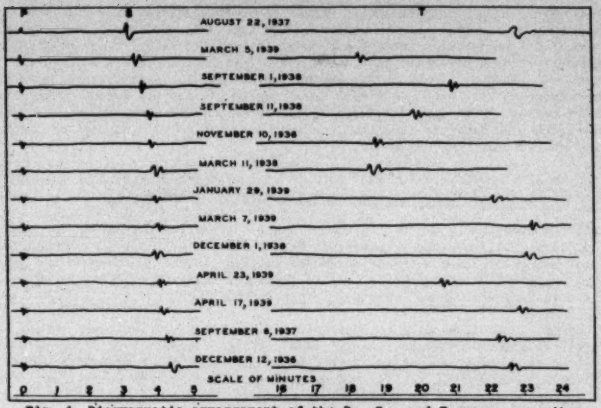

Fig. 4--Diagrammatic arrangement of the P-, S-, and T-groups according to increase in (S-P)-interval

stronger quakes there is a fourth group, also transverse, that follow about four minutes after the third group. In the 50 odd quakes studied there has been only one quake that demonstrated surface-waves.

The P-group from three quakes recorded by the vertical short-period component at Weston are placed together in Figure 2. Each represents a different distance but the characteristics are similar. The first one of March 5, 1939, is 17°2 distance, the second of March 17, 1939, is 21°3 distance, and the third of December 1, 1938, is 23°5 distance. Note also on the third quake that it is led by an impulse about 35 seconds before the first group. This impulse belongs to an entirely different quake of some 80° distance. At first sight one might think that the instrument recording these quakes was underdamped, but actually the damping is critical at all times.

Figure 3 demonstrates the three components of the P-group for the quake of March 5, 1939. During the first nine seconds the records show that the vertical and the north-south components are identical and show clearly the epicenter to the south. The amplitudes are approximately the same, although the actual instrumental magnification of the horizontal component is weaker, demonstrating that the angle of emergence is small. The group on the east-west component is about six seconds late, as would be expected in the present azimuth. Throughout the recording of the group this component is always the weakest.

Although an illustration of the S-group is not presented here, an examination of the original grams shows definite polarization. Again the azimuth is well demonstrated by the late arrival of this phase on the north-south component with respect to the east-west. The transverse character of the wave is also emphasized. The sustained greater amplitude on the transverse component is also brought out. This latter characteristic is always present.

Figure 4 shows a diagrammatic arrangement of the P-, S-, and the T-groups. Approximately ten minutes are omitted by the break in the diagram. The quakes are arranged according to the increase in the (S-P)-interval. They do not appear to be a function of this interval. If there is any functional quality, it appears to be inverse, such as many of the core-waves whether reflected or refracted, but the discontinuity of this function as appears about half-way down Figure 4 is quite amazing.

In a recent private communication with the Honorable R. C. Hayes of the Dominion Observatory, Wellington, New Zealand, he states his belief that these quakes are of deep focus and that the third group are of the ScS-type, and the fourth group mentioned above would be sScS, or the former reflected from the Earth's crust before being reflected from the core. Unfortunately, I could not give him all the other data, such as low angle of emergence, etc., before he made this statement. I feel that such would eliminate their being of deep focus. In Bulletin No. 107 of

the Dominion Observatory he has determined the depths of several quakes using the (sScS-ScS)-interval. The azimuth of his station with regard to the quakes he studied is identical with the azimuth of Weston to the West Indian Region, and many similarities exist in the records. However, this third or T-group arrives too late to be classified as ScS, and if we used the interval mentioned for depth we would find many of the depths very great. For example, the quake of June 12, 1939, with an interval for these two groups amounting to 240 seconds would give a depth of about 500 km. One reason why it should not be considered deep is because none of the many stations which reported it--we have the readings from over 40--even up to distances of 154° refers to any deep-focus characteristics.

Most of the travel-time tables examined are bare of any phases occurring at this instant and it is probable that we shall have to deal with a new phase before the studies are completed.

As was mentioned above, only one of the quakes studied presented surface-waves, namely, the quake of June 12, 1939. This one did present such waves with periods up to 25 seconds, but the amplitude of these was by no means what one would expect from the energy shown in the preliminary phases. The half amplitude of the P-phases in this quake were over 50 millimeters on the Weston records, while the surface-waves were less than half that amount.

Quake of June 12, 1939--It seems quite necessary that a set of travel-times should be constructed for this area and the quake of June 12, 1939, offers fine opportunity for this work. The San Juan station is perhaps closest to the epicenter with a distance of 270 km and we have other fine readings of P- and P' up to 154°. Many of the station-records have already been gathered by the author, but because of other pressing duties, this study has not been completed.

Summary--It is the hope of the author that other stations with short-period instruments of high magnification may be established nearer to the West Indian Region than the present group at New England, to make a better location of the very many earthquakes that are taking place there. He feels it is important in the light of recent interest in tectonics and believes a study of the possible movements along the gravity-arc near the West Indies will offer great aid to this study.

Weston College,
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THE VIEQUES, PUERTO RICO, SEISMOGRAPHIC RECORD OF THE DESTRUCTIVE EARTHQUAKE OF 1918 AS A CLUE TO LOCAL CRUSTAL STRUCTURE

Frank Neumann

(Abstract)

An (S-P)-interval of 17 seconds is recorded for the main shock and a number of aftershocks. According to recent ideas concerning travel-times in continental structure, this would correspond to a distance of 135 to 160 km depending upon focal depth. But we know from Reid and Taber's very thorough investigation that the epicentral distance from Vieques must be 195 km and possibly more. This calls for velocities of P and S which would exist only if a very large part of the continental structure were missing, that is, a structure somewhat like the Pacific. A feature of the records is that the surface-waves have the (slow) velocity to be expected in granite and are quite strong, showing that while a layer of granite is probably present, it is too thin to appreciably affect the travel-times of the interior waves as it does in normal continental structure.

U. S. Coast and Geodetic Survey,
Washington, D. C.

SOME POINTS OF GEOPHYSICAL INTEREST REVEALED IN THE MASS-ANALYSIS OF TELESEISMIC RECORDS

R. R. Bodle

Mass-analysis of seismograms may at first glance sound uninteresting. As a matter of fact to the casual observer of the subject this is no doubt quite true. When one is in continuous contact with the interpretation of seismograms the reverse is very apt to be true. The picture that one gets under these circumstances might well be compared to the old picture-puzzle with

Table 1--Supporting data for Gutenberg - Richter travel-times

Station	Geocentric-latitude distance	Δ by P-H based on geocentric latitude gives values too short (-) or long (+)	H must be later (+) or earlier (-) to obtain computed Δ	Rate of travel
	km	km	sec	km/sec
Ukiah	473	- 73	- 9	7.93
Sitka	1708	- 64	- 8	8.56
College	2803	- 59	- 5	12.3
New York (Fordham)	4227	- 16	- 1	12.3
Weston	4242	- 75	- 7	12.3
E. Machias	4579	- 43	- 3	13.1
Butte	1087	+ 19	+ 2	7.92
Pasadena	1174	+ 4		7.93
Bozeman	1194	+ 17	+ 2	7.93
Tucson	1760	+ 7	+ 1	8.54
St. Louis	2997	+ 14	+ 1	12.3
Little Rock	2999	+ 1		12.3
Chicago	3102	+ 9	+ 1	12.3
Honolulu	3835	+254		12.2
Georgetown	4050	+ 17	+ 2	13.4
Burlington	4149	+ 29	+ 3	13.2
Philadelphia	4158	+ 20	+ 2	13.2
Williamstown	4207	+ 15	+ 1	12.33
Kew	8291	- 19	- 1	20.0
De Bilt	8460	+ 56	+ 3	20.0

hidden faces to be found. By careful observation one can eventually find all of them. The same is true in seismology though the faces are exchanged for geophysical facts.

Data from 18 seismograph stations are now published by the United States Coast and Geodetic Survey (see Table 1). The records from nearly all of them are directly available in one place, thus offering an opportunity rarely, if ever, found elsewhere, and is a decided advantage since it permits direct checking on the value and accuracy of the records. It has been my privilege to be associated with this work for a number of years. As time passes the seismological picture becomes more familiar and certain significant points become apparent as in the case of the old picture-puzzle.

The problem of regional variation in travel-times of seismic waves has been gradually emerging. I say regional variation for lack of a better name and complete understanding of their nature. Some seismologists are skeptical of their reality. The author is becoming convinced as time goes on that they are real even though a complete explanation has by no means been reached. Landsberg and Neuberger have approached the problem from the statistical point of view and have concluded that seismic travel-times vary over rather wide areas.

The writer has approached the problem from the standpoint of individual shocks where time-differences are probably higher since they are not "rounded off" as a result of the statistical treatment. This method of approaching a seismological problem is not new as many investigators have used it in recent years. From the nature of the data confidence can only be placed in data indicating early arrival at the seismic station as compared with late arrival-times which are usually emergent on the records. In verbal discussion, both Jeffreys and Richter have suggested that early arrivals may be the result of foreshocks.

While reviewing data for publication a few days ago an earthquake which produced data tending rather conclusively to refute the possibility of foreshocks was found. Figure 1 indicates the arcs drawn on a 30-inch globe. They are based on travel-times given in the Gutenberg-Richter tables. Note the arcs for Sitka and College, Alaska, are both short. The Ukiah distance is also short.

At once the question of accuracy of epicenter will present itself--but for this once, at least, the felt-effects on shore tend to confirm the adopted instrumental location.

With this assurance that the instrumental location is reasonably correct, one would expect a foreshock to register at Pasadena as well as at Sitka, College, and Ukiah.

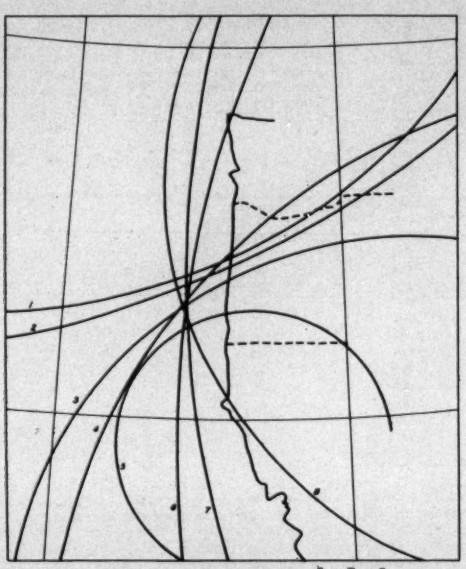

Fig. 1--May 28, 1938: $H_{P-H} = 10^h\ 14^m\ 05^s$
[1 = Sitka; 2 = College; 3 = Pasadena; 4 = Tucson;
5 = Ukiah; 6 = Little Rock; 7 = St. Louis; 8 = Bozeman]

It is therefore not unreasonable to conclude that variations such as these are real and must have geophysical significance. The picture in the puzzle is beginning to appear but more observation will be necessary to determine the true outline of its significance. Indications obtained by previous investigations point to a rather narrow belt stretching along the edge of the Pacific Ocean, perhaps from California to the Western Aleutian Islands.

U. S. Coast and Geodetic Survey,
Washington, D. C.

THE STEREOGRAPHIC PROJECTION WITH PRIMITIVE RADIUS OF 50 CENTIMETERS

F. W. Sohon

Joseph F. Cohalan, S.J., formerly at Georgetown University and now at Woodstock College, Maryland, in his master's dissertation entitled "The seismologist's problem and the method of Saint Hilaire," studied the question of securing a more open scale for the graphical determination of epicenters from reported epicentral distances. He found that the use of navigator's plotting charts was not practical, but that a stereographic projection with a primitive radius of 50 cm was very promising. This allows 4.4 mm for a degree at the center of the map, and an area 40° each way in latitude and longitude can be constructed on an ordinary typewriting sheet. Throughout this area 1/64 inch = 10 km.

We have to compute the great circle distance Z, and the azimuth A, of the various stations from the adopted primitive zenith-point. If φ = latitude of the observing station, λ = longitude of the observing station, Φ = latitude of the primitive zenith, and Λ = longitude of the primitive zenith, then A and Z can be obtained from the formulas

Table 1--Cohalan's primitive zenith-points

No.	Primitive zenith		OP	OP'	Earthquakes per cent	
					Total	Major
	°	°	cm	cm		
1	60 N,	180	13.40	186.60	3.8	4.1
2	20 S,	180	71.41	35.01	7.5	7.8
3	60 N,	140 W	13.40	186.60	2.7	2.8
4	20 N,	100 W	35.01	71.41	5.7	8.3
5	20 N,	60 W	35.01	71.41	3.2	3.7
6	50 N,	20 W	18.20	137.37	3.6	0.8
7	40 N,	20 E	23.32	107.23	10.5	6.9
8	30 N,	60 E	28.87	86.30	6.9	5.1
9	40 N,	100 E	23.32	107.23	5.1	3.7
10	0 ,	100 E	50.00	50.00	5.6	5.9
11	40 N,	140 E	23.32	107.23	12.9	14.5
12	0 ,	140 E	50.00	50.00	13.0	20.0
13	50 S,	10 W	137.37	18.20	1.0	0.8
14	20 S,	80 W	71.41	35.01	5.8	7.1
15	20 S,	50 W	71.41	35.01	1.2	0.7
			Totals		88.5	92.2

$$\tan M = \tan \varphi \sec (\lambda - \Lambda)$$
$$\tan A = \tan (\lambda - \Lambda) \cos M \csc (M - \Phi)$$
$$\tan Z = \tan (M - \Phi) \sec A$$

using as a check

$$\cos \varphi \sin (\lambda - \Lambda) = \sin A \sin Z$$

In order that this preliminary computation may be done once and for all, it is necessary to adopt standard primitive zenith-points. To select these points, Mr. Cohalan made a study of the geographical distribution of epicenters from Captain Heck's list. Table 1 shows the location of his adopted primitive zenith-points, together with the percentage of total, as well as the percentage of major earthquakes in Captain Heck's list that do not differ in latitude or longitude by more than 20° from his own selected points. The columns headed OP and OP' give the radial distances in centimeters to the projected north and south poles, respectively.

To draw the circles of position, compute for each observing station

$$\tan [(Z - A)/2]$$

and

$$D = \tan [(Z + A)/2] - \tan [(Z - A)/2]$$

where Z is the primitive zenith-distance of the observing station and A is the reported epicentral distance. The technique adopted involves the use of a semicircular protractor having a diameter of eight inches, and a triangular metric scale carrying half-size and quarter-size scales. The line of measures is drawn for each station in the azimuth of that particular station. Along the line of measures, positive intervals are laid off toward the station, and negative intervals are laid off away from the station. Lay off on each line of measures the distance

$$ON = 50 \tan [(Z - A)/2]$$

which is done by plotting the natural tangent directly with the half-size scale. If

$$\left|\tan [(Z + A)/2] - \tan [(Z - A)/2]\right| < 2.9$$

the radius of the required circle of position

$$NC = 25 \left\{\tan [(Z + A)/2] - \tan [(Z - A)/2]\right\}$$

is laid off along the line of measures from N, giving us the point C, which is the center of the required circle. Multiplication by 25 is not necessary, for the difference of the two natural tangents can be plotted directly with the quarter-size scale. Then with C as center and with CN as radius, in each case, the projected circles are to be drawn in. If, however,

$$|D| = \left|\tan [(Z + A)/2] - \tan [(Z - A)/2]\right| > 2.9$$

the circle is nearly a straight line, and will be ruled along the face of a spline bent by means of pure end-torques to pass through three known points of the required circle. The circle must pass through the point N. Two other points on the circle are found as follows: Table 2 gives for different values of the quantity D the angle between a tangent line and a four-inch chord for the radius of the circle in question. Enter Table 2 with D and come out with the angle θ. Place the protractor with its base at the point N and its 90° division on the line of measures, pointing toward the station if D is positive, away from the station if D is negative. Prick points at the edge of the protractor at the readings θ and (180° - θ). The circle of position to be drawn must pass through these two points as well as the point N.

Having spotted the projected epicenter from the intersections of the arcs, its rectangular coordinates X and Y are measured in centimeters, and the coordinates of the epicenter are ob-

Table 2--Angle between tangent line and four-inch chord for circles whose radii are given in quarter meters

0.0	0.7	1.4	2.0	2.7	3.4
232.8506	15.5239	8.0302	5.6805	4.2353	3.3767
0.1	0.8	1.5	2.1	2.8	3.5
77.6170	13.6976	7.5122	5.4164	4.0863	3.2817
0.2	0.9	1.6	2.2	2.9	3.6
46.5703	12.2559	7.0571	5.1758	3.9484	3.1919
0.3	1.0	1.7	2.3	3.0	3.7
33.2646	11.0888	6.6540	4.9557	3.8191	3.1069
0.4	1.1	1.8	2.4	3.1	3.8
25.8726	10.1247	6.2944	4.7535	3.6980	3.0264
0.5	1.2	1.9	2.5	3.2	3.9
21.1686	9.3148	5.9717	4.5673	3.5843	2.9498
0.6	1.3	2.0	2.6	3.3	4.0
17.9120	8.6249	5.6805	4.3950	3.4774	2.8771

tained by means of the formulas

$$\tan \psi_1 = X/(OP - Y)$$

$$\tan \psi_2 = X/(OP' + Y)$$

$$\tan [(\varphi - \Phi)/2] = 0.02 \quad Y - X \tan [(\psi_1 - \psi_2)/2]$$

$$\lambda - \Lambda = (\psi_1 + \psi_2)$$

Attached to his dissertation, Mr. Cohalan gives tables for the polar coordinates of the centers and for the radii of the projected meridians and parallels, so that the computer can embellish his construction by drawing these in. The construction should be made using geocentric latitudes, but the final parallels to be drawn in should be geographical latitudes. Mr. Cohalan's tables would give the geocentric network, but it seems desirable to compute the elements for a geographic network. This is now being done.

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Washington, D. C.

A DYNAMIC TESTER FOR GALVANOMETRIC SEISMOGRAPHS

H. E. McComb and J. H. Nelson

(Abstract)

When a Wenner seismograph was sent to the Office from one of the United States Coast and Geodetic Survey seismograph stations for repair and cleaning it was found that the sensitivity of the instrument varied considerably with the drifting of the boom away from the center position. This condition suggested the desirability of having some simple method of testing the relative sensitivity from time to time--daily if necessary--without disturbing the seismometer and galvanometer and with a minimum loss of record. The scheme developed was the dynamic tester.

Very briefly, the dynamic tester consists of a control-box so arranged that by the operation of a single switch the operator may disconnect the seismometer from the galvanometer and apply a small known voltage to the terminals of the seismometer. This will, of course, cause the boom to be deflected from its normal position of rest; at the same time the galvanometer will drift to its zero-position. Upon snapping the switch to operating position the seismometer is disconnected from the source of electromotive force and almost instantaneously reconnected to the galvanometer. As the boom swings from its deflected position back to the normal position the galvanometer is deflected and displacement is recorded on the seismogram. The amplitude of the displacement is a measure of the sensitivity of the seismograph, and when used over a period of several months the test should show up any changes of sensitivity that might occur.

The tester and its operation have not as yet been analyzed mathematically, and its action therefore has not been described quantitatively. It has, however, been in routine use at one observatory with apparently satisfactory results.

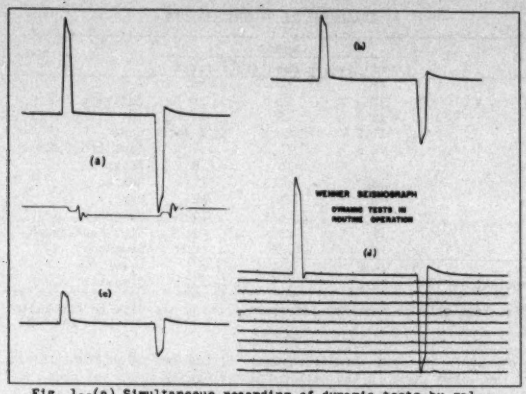


Fig. 1--(a) Simultaneous recording of dynamic tests by galvanometer and by mirror mounted directly on seismometer-boom (slightly displaced on time-scale); applied reference-voltage = 1.50
(b) Dynamic tests; applied reference-voltage = 1.00
(c) Dynamic tests; applied reference-voltage = 0.50
(d) Wenner seismograph dynamic tests in routine operation

U. S. Coast and Geodetic Survey,
Washington, D. C.

SOME SEISMIC CONTRIBUTIONS TO KNOWLEDGE OF THE EARTH'S CRUST

N. H. Heck

Some very positive facts about the Earth have come from seismology. These include: The existence of a quite sharply defined core; the possibility of quite accurate location of normal-depth earthquakes, because the transmission-time of the same kind of waves through the Earth is approximately the same for the same distance in all parts of the Earth; the occurrence of deep-focus earthquakes and determination of their depth; and finally the occurrence of high-speed surface-waves over the Pacific Basin.

The evidence regarding the surface-layers, considering the Earth as a whole, is less positive than conclusions regarding the interior. There is a difference of opinion as to the validity of the establishment of crustal layers of similar thickness over wide areas. Views range from those of Macelwane, who considers the crustal conditions as quite local, to those of others who believe that layers of similar thickness may cover a wide extend of area. The difficulty lies in the fact that velocities measured at the surface only are available and that in only a few localities are the seismograph installations capable of furnishing observations of the needed accuracy. However, such observations have been supplemented by those from nigh explosions. The most widely adopted interpretation is the two-layer theory. Table 1 gives the principal published results.

First consider two areas in California where the observations are adequate. In the San Francisco Bay region Byerly deduces two layers of 9 and 23 km, respectively, and finds--as Gutenberg--that the thickness of the upper or so-called granitic layer increases toward the south, where Gutenberg found a granitic layer of 14 km and a lower layer of 25 km which gave some evidence of separation into several layers.

For the eastern part of the United States, Leet finds that a granitic layer 14.5 km thick fits most of New England, while Slichter in the Connecticut Valley found no discontinuity till a

Table 1--Thickness of crustal layers

Locality	Layers			Author
	Granitic	Intermediate	Total	
	km	km	km	
Central Europe	10	20	30	Jeffreys
Northern Europe	14	15	29	Lee
Balkans	11.5	22-33	33.5-44.5	Lee
India	14.5	....	....	Geological Survey of India
Japan	0	16	16	Hodgson
New Zealand	0.7	16.5	17	Bullen
Central California	9.	23	32	Byerly
South California	14	11-6-8	39	Gutenberg
Missouri	16	13	29	Miss Robertson[a]
New Jersey	15	....	....	Neumann
New England, General	14.5	....	....	Leet
New England, Connecticut Valley	23.5	....	....	Slichter

[a]With the proviso that this is the best interpretation of the data on the basis of a two-layer crust.

depth of 23.5 km was reached. It might then be assumed, if the two-layer-crust theory is valid, that the thickness of the upper layer in the eastern United States is on the order of 15 km and that the bottom of the lower layer is at 30 to 40 km below the surface. There is, however, another possibility. Byerly has found, in the Sierras of southern California, seismic evidence that there is a granitic root extending down perhaps to a maximum of 71 km whereas the granitic layer in general is only about 15 km thick.

The possibility is suggested that there may be greater thickness of crust under other mountains (see Table 1 for thickness in the Balkans) and among these the Appalachians. At present the evidence is almost wholly lacking since suitable observations have not been made. The significance of the difference in results in New England between Leet and Slichter has not yet been determined. Without drawing any inference as to its significance it should be pointed out that the isoseismal lines for the Charleston (1886), St. Lawrence (1925), and Temiskaming, Canada (1935), earthquakes all show a large area in the Appalachians where the earthquakes are felt with much less intensity than for equal distance from the epicenters in other directions.

I am not going into the subject of isostasy but simply point out that the Airy hypothesis calls for roots of the mountains, that is, a greater thickness of the crust beneath the mountains and the similarity of this to Byerly's findings is of interest. The Pratt hypothesis on the other hand calls for compensation at the same depth whether beneath oceans, lowland, or mountain area. There is difficulty in settling the issue between the two hypotheses because a satisfactory depth can be computed only for areas with a considerable change in elevation. Bowie, who has done much to establish the Pratt hypothesis, states in a recent article "it is not known definitely how far down the compensation extends, nor whether the depth is the same for different parts of the Earth."

It is regrettable that conditions do not permit the study of the deep crustal structures in the Himalayas.

The next question is what happens as we pass from the continent to the Atlantic Basin. Gutenberg has long held that the Atlantic and Indian oceans have about half the thickness of crust of the continents. In a recent article he has modified his views to the extent of stating that the structure in these oceans is similar to that under the continents but much thinner.

There is some recent evidence from records at a newly established station at Bermuda that surface-waves from earthquakes with an all mid-Atlantic path have almost the same speeds as for the Pacific.

In spite of Gutenberg's view that other lines of evidence tend to confirm the picture of the crust which he has advanced I feel that pending the receipt of a number of satisfactory records from Bermuda, a mid-Atlantic crustal condition like the Pacific cannot be rejected.

Whatever theory of continental and suboceanic crustal structure is adopted, there must be a transition from one to the other. The evidence is in favor of gradual transition in the case of the Atlantic. A sudden deep-seated change would undoubtedly have some surface-topographic ex-

pression. Detailed surveys by the Coast and Geodetic Survey indicate absence of abrupt changes which could be related to seismic effects and Ewing's profile of the basement-rock off the Capes of Virginia gives similar results though neither fact provides conclusive evidence. Stronger confirmation comes from the absence of a seismic belt, though the Charleston (1886) and the Grand Banks of Newfoundland (1929) earthquakes need explanation.

The pattern for the Pacific Basin is markedly different. There are mountain belts close to the shore, in some places long rifts, and in others deep ocean-troughs not far from the shore. The major earthquake-belt of the Earth follows the rim of the Pacific. Gutenberg has found that there is a vertical surface of discontinuity at the edge of the Pacific of unknown depth but possibly that of the continental crust. Byerly and the Coast and Geodetic Survey have found evidence that the extensive San Andreas Fault may turn off to sea at Cape Mendocino and stop when it meets the ultrabasic conditions of the Pacific Basin, and the earthquake-evidence does not contradict this conclusion.

It is sometimes claimed that earthquakes may be related to changes in the crust of very wide extent. This cause would seem to be specially appropriate to the widely felt earthquakes which occur from time to time in the eastern United States and Canada. A special cause of such movements might be the recovery from the pressing down of the crust due to the great ice loads of quite recent geological time. It is well determined that there was such an effect in Scandinavia where the great extent of coast-line and slowly eroded rock provide favorable conditions for measurement. Under the conditions of eastern North America can geophysical measurements definitely determine such movements? The evidence is not very complete nor conclusive.

C. K. Gilbert from gage-readings decided that the Great Lakes Region was tilting toward the southwest at the rate of 0.0042 foot per mile per century. The entire effect was so small over the period of observation that Hayford was doubtful of its reality since Gilbert overlooked certain meteorological effects on lake-levels. However, old shore-lines have been found to be tilted and Delaney at Canisius College, Buffalo, has through tilt-measurements found a continuing tilt from north to south. Before discussing the tidal evidence along the eastern United States it should be pointed out that for most of the region where recovery from the ice-load might be expected there are drowned river-valleys and generally sandy shores where most of the geological record of change is lost. The question of change in sea-level through increase or decrease of polar ice does not seem to enter the problem since the effect should be the same at all stations.

Over a period of centuries the tidal evidence would be conclusive as to differences in elevation of different parts of the coast, but there are difficulties. The period of satisfactory automatic tide-observations at a reasonable number of stations has not been great, there is difficulty with loss of and shifting of bench-marks, and there are meteorological effects on the tides. However, Marmer of the Coast and Geodetic Survey finds some evidence of trends continuing in the same direction. It might be asked whether precise leveling between bench-marks repeated from time to time, would help solve the problem. The difficulty is that, while the levels are precise enough for most purposes, this requires very great accuracy over long distances. Commander C. L. Garner, Chief of the Division of Geodesy of the Coast and Geodetic Survey, appraises the situation as follows:

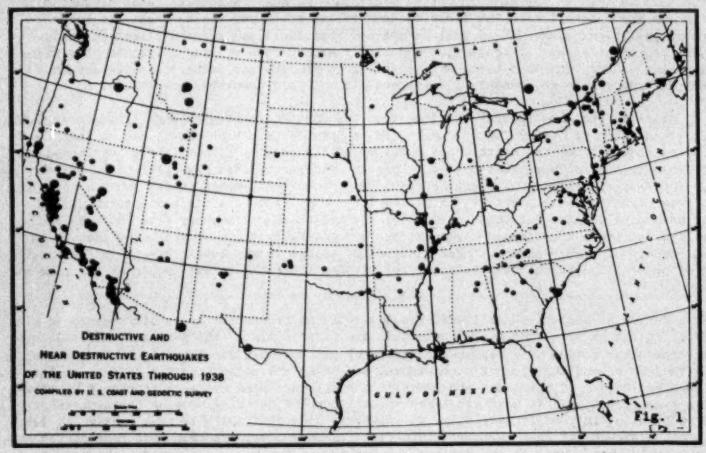
"A network of first-order leveling extending over the United States and adjusted to a rigid datum shows that sea-level in the vicinity of Boston is about a foot higher than at Fernandina, Florida; at Galveston, about a foot higher than at Fernandina; and the Pacific Ocean about two feet higher than the Atlantic. This leveling, however, was done over a period of some 50 years and was not for the specific purpose of examining the differences in elevations of the Atlantic, Pacific, and Gulf levels. There is some speculation with regard to the possibility of obtaining more conclusive results through observations made specifically for that purpose over a short period of time. The difficulty here, as with many other similar problems, is the cost."

We shall now look at the earthquake-map of the region (see Fig. 1) to see whether there are facts of special significance. First, there is a general trend shown by earthquakes of intensity V, Rossi-Forel scale, or over. Note the belt that extends from New Brunswick, Canada, to Alabama, generally along the edge of the mountain area, which meets the New England belt near the coast and further southwestward of the Atlantic Coastal Plain. Thus, New Jersey has a fair number of earthquakes while Pennsylvania has very few. There is the belt that extends from the St. Lawrence Valley to Mississippi. It should be noted that the only connection between the two belts is in the Hudson Valley and the Lake Champlain Region. The absence of earthquakes in the mountains of Pennsylvania and West Virginia must possess an important significance. This is so marked that the Blair County, Pennsylvania, shock of July 15, 1938, while of little importance

as an earthquake, was an outstanding seismic event for the Region.

It should also be pointed out that many of the eastern North American earthquakes have the unusual feature that they are felt over a very large area and the central region of maximum intensity, which is ordinarily not very high, is also large. This suggests that the release of energy is spread over an area of considerable extent so that it is very hard to locate them accurately from the seismograph records. Accordingly some of the more wide-spread earthquakes are of little use in providing information about the crust.

When all the earthquakes are plotted there is evidence of another belt along the Atlantic Coast from New Jersey southward. Most of its earthquakes are minor, such as those that have recently occurred in New Jersey, but, surprising enough, it includes one of the greatest earthquakes of the United States--that of 1886 of Charleston, South Carolina. This had the astonishing feature that there were no foreshocks of importance and no very severe aftershocks. Its significance demonstrates the impossibility of definite assurance that earthquakes will not occur anywhere, and the Timiskaming earthquake of 1935 on the Canadian shield and the Baffin Bay earthquake of 1933 on the same general formation support this view.


DESTRUCTIVE AND
NEAR DESTRUCTIVE EARTHQUAKES
OF THE UNITED STATES THROUGH 1938
COMPILED BY U. S. COAST AND GEODETIC SURVEY
GULF OF MEXICO
Fig. 1

My purpose has been to outline a number of problems regarding the Earth's crust, most of which are unsolved. Solution will come if at all by geophysical methods, though in some cases it will be necessary to wait a long time for the solution.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A NEW METHOD FOR DETERMINING THE EPICENTER OF A NEAR EARTHQUAKE

Henry F. Birkenhauer

(Abstract)

An original mathematical method was devised for locating the epicenter of the Illinois earthquake of November 23, 1939. The azimuth of this earthquake from St. Louis was found from the horizontal components of the ground-displacement according to the method of Galitzin. The quantity (t'/t'') where t' is the arrival time of $\bar{P}$ at Florissant minus the arrival-time of $\bar{P}$ at St. Louis, and t'' is the arrival-time of $\bar{P}$ at Cape Girardeau minus the arrival-time of $\bar{P}$ at Florissant, was known. Since the $\bar{P}$-curve is a straight line for near earthquakes, $(t'/t'') = (\Delta'/\Delta'')$ where Δ' is the corresponding difference in epicentral distance between Florissant and

St. Louis and Δ'' is the difference in epicentral distance between Cape Girardeau and Florissant. The point on the azimuth-line from St. Louis for which $(t'/t'') = (\Delta'/\Delta'')$ was found to be 38° 02' 15".74 north, 90° 04' 3".64 west in geocentric coordinates, a location which agreed well with the macroseismic data.

Department of Geophysics, St. Louis University,
St. Louis, Missouri

LONGITUDINAL WAVE-VELOCITIES IN THE MISSISSIPPI VALLEY

Edward J. Walter

(Abstract)

An investigation of the seismicity in the Mississippi Valley near St. Louis was undertaken by the autnor. The plan of the investigation was to study the records of near earthquakes as recorded at St. Louis and its affiliated stations. The shocks were soon sifted down to six, from which the data were to be taken.

The epicenters as previously determined were accepted as approximately correct. The observed phases were plotted as arrival-times against calculated distances for each earthquake and a least-squares solution made for each. Three average index-velocities were determined. They are 6.03, 6.33, and 7.73 km per second, respectively. The calculated distances were then corrected on the basis of the average velocity in the upper layer and an epicentral time for each earthquake, determined from the least-squares solution for the velocity-curve in the upper layer.

All P-phases for all six earthquakes were then plotted as (P-E)-intervals against the corrected distances. The alignment of a series of phases in a straight line yielded a fourth curve, displaying a velocity of 7.19 km per second. We then have four longitudinal wave-velocities, 6.03, 6.33, 7.19, and 7.73 km per second, respectively, with their structural implications which the author is at present investigating.

Department of Geophysics, St. Louis University,
St. Louis, Missouri

GEOLOGICAL SEISMOGRAPHY

R. M. Field

My remarks pertain to the application of seismography to geological surveying. Captain Heck's paper is particularly pertinent, especially as it is an excellent summary of the real contributions which our Special Committees of the Union have made in such a significant phase of geophysics during the past three or four years. The points which I should like to emphasize are as follows:

(1) Seismography is the earliest of geophysical techniques directly applied to the study of the composition and structure of the Earth. This has been recognized in most text-books of general geology from the time of Sir Charles Lyell.

(2) Until recently the art and technique of seismology has been restricted to the study of earthquakes, or natural vibrations, with the result that the principal contributions of seismographers have been to our knowledge of the composition and structure of the subcrustal "zones". This is all the more interesting, historically, because the father of British seismography, Robert Mallet, produced artificial "earthquakes" by means of gun powder; and even proposed that this method could be used to determine the media velocities of submarine formations, from coastal waters to oceanic depths. This artificial method, so useful to the study of the crust, remained dormant until developed by the petroleum geologists and geophysicists for discovering structural oil-traps; and it is only within the past five years that any serious and cooperative attempt has been made to apply this method to the study of the structure of the continental and suboceanic lithosphere.

(3) It is greatly to the credit of the Union that, through the cooperation of the Section of Seismology with the Special Committees on the Geophysical and Geological Study of Oceanic Basins and of Continents, seismography, and especially "induced seismography", has been applied to fundamental problems in continental and submarine geology.

The history of seismography shows that, since the time of Mallet (with the exception of the excellent work of the petroleum geologists and geophysicists), this important geophysical art has become too sedentary; and, with one or two exceptions, most individuals and institutions have devoted their seismographical efforts to the development, installation, and operation of fixed instruments which are entirely dependent upon natural vibrations. Further, the location of those stations has necessarily been governed largely by the geographic coordinates of universities and colleges, and not by the theories and practice of seismology. Much has been accomplished in remedying this deficiency by the work of our Section of Seismology, the International Association of Seismology, and the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics. In this case, again, the particular stimulus has come from a few paleo-geographers and structural geologists who, appreciating the pioneer studies of Jeffreys and Gutenberg, have helped to promote the installation of new stations, particularly in seismic belts and on oceanic islands. The recent installation of the Bermuda Station is an excellent illustration of international cooperative research among seismologists, oceanographers, and geologists. Unfortunately, the increasing disturbance in Europe will probably seriously interfere with, if not entirely destroy, the work of the Bermuda Station for some time to come--if not permanently. It takes much labor and time to develop international cooperation in the Earth sciences, and such an unfortunate and probably complete relapse as we are to see this year is a serious blow to suboceanic seismography, and, therefore, to the geology of the suboceanic crust.

The paper by Captain Heck [see these Transactions, pp. 237-240] reviews recent progress in geological seismography, and, together with the preliminary report of the Commission on Continental and Oceanic Structure, already published, should serve to summarize the endeavors and accomplishments of the American Geophysical Union and the International Union of Geodesy and Geophysics to date. This is, unfortunately, not the time to over-emphsize the importance of national and, especially, international cooperation in fundamental science, or that complete coordination of seismological and geological surveys essential to our better understanding of the major problems in paleogeography and structural geology. I should like, however, to repeat my belief that the Section of Seismology should actively promote further exploration by means of induced or artificial seismography, and particularly instrumental research, such as has been found so effective by the petroleum geologists. Also, that, while more seismographic observations for the study of natural vibrations are badly needed in certain specified areas, seismologists, seismological societies, and seismological laboratories should explore more thoroughly the application of seismic surveys to geological problems, especially those of the suboceanic crust; for I am sure that such procedure will not only be of immense benefit to Earth science, but will also redound particularly to the benefit of seismography and the science of seismology, as a whole.

Princeton University,
Princeton, New Jersey

PROGRESS-REPORTS

JESUIT SEISMOLOGICAL ASSOCIATION FOR 1939

James B. Macelwane

The cooperative arrangement between Science Service, the United States Coast and Geodetic Survey, and the Jesuit Seismological Association has been fruitfully continued. During the past year a total of 55 epicenters were tentatively located and 51 preliminary bulletins were mimeographed and mailed directly to about 375 institutions and interested individuals in all parts of the world.

In so far as possible, the approximate focal depths were determined for each of the earthquakes for which preliminary bulletins were published. The distribution of these depths is interesting. Of the earthquakes thus located 33 had a focal depth less than 50 km, seven a focal depth between 50 and 100 km, eight between 100 and 200 km, two between 500 and 600 km, and one each between 200 and 300, 300 and 400, and 600 and 700.

The following stations of the Association have been contributing data to the Preliminary Bulletin during the past year: Buffalo, Cape Girardeau; Chicago (Loyola); Cincinnati; Denver; Florissant; Fordham; Georgetown; Little Rock; Saint Louis; Santa Clara; Spokane (Mount Saint Michael's); and Weston.

The United States Coast and Geodetic Survey has contributed regularly and very promptly to the Preliminary Bulletin not only the data from its own stations at Chicago, Honolulu, San Juan, Sitka, Tucson, and Ukiah, and from the cooperative stations at Bermuda, Butte, Bozeman, Columbia, East Machias, Lincoln, and Salt Lake City, but also from many other stations, and particularly from Manila and Apia whose data are transmitted by radio through the courtesy of the United States Navy.

The equipment of the Jesuit stations has not been modified significantly during the past year except that at Saint Louis the long-period Wood-Anderson seismographs were transformed into short-period seismometers by the insertion of short-period suspensions and two of the seismographs which were used in the research on microseisms were turned into routine long-period instruments by lengthening the period of the pendulum from six to 20 seconds and by substituting for the six-second Leeds and Northrup, type-R galvanometers a pair of 20-second Leeds and Northrup HS galvanometers. All four seismographs are giving excellent service.

Department of Geophysics, St. Louis University,
St. Louis, Missouri

UNIVERSITY OF CALIFORNIA SEISMOGRAPHIC STATION FOR YEAR ENDING APRIL 30, 1940

Perry Byerly

Progress at the seismographic station of the University of California for the year ending April 30, 1940, is indicated by the following list of papers:

[1] Perry Byerly, Near earthquakes in Central California, Bull. Seis. Soc. Amer., v. 29, No. 3, July, 1939.
[2] Perry Byerly, Speeds of seismic waves and Earth structure in Central California (abstract), Bull. Geol. Soc. Amer., v. 50, No. 12, Part 2, December, 1939.
[3] Perry Byerly, Earthquake epicenters and structure of the Pacific Region of North America (northern part), to appear in Proc. Sixth Pacific Sci. Cong., held August, 1939.
[4] Perry Byerly, Seismicity of the Northern Pacific Coast of the United States, Bull. Geol. Soc. Amer., v. 5, No. 1, February, 1940.
[5] Perry Byerly, Microseisms at Berkeley and surf on nearby coasts, paper read before the International Commission for the Study of Sea Waves of the International Union of Geodesy and Geophysics, Washington, September, 1939, to appear in Annales de la Commission pour l'Etude des Raz de Maree.
[6] Perry Byerly and Horace Miller, Earthquakes in Northern California and registration of earthquakes at Berkeley, Mount Hamilton, Palo Alto, San Francisco, Ferndale, Fresno, from January 1, 1938, to March 30, 1938, Bull. Seis. Stations, Univ. Calif., April, 1940.

[7] James T. Wilson, The surface waves of the South Atlantic Earthquake of August 29, 1933, to be published in Bull. Seis. Soc. Amer.
[8] John N. Adkins, The Alaskan earthquake of July 22, 1937, to be published in Bull. Seis. Soc. Amer.
[9] Perry Byerly and Horace Miller, Earthquakes in Northern California and registration of earthquakes at Berkeley, Mount Hamilton, Palo Alto, San Francisco, Ferndale, Fresno, from April 1, 1938, to July 1, 1938, in press.
[10] Perry Byerly and Horace Miller, Earthquakes in Northern California and registration of earthquakes at Berkeley, Mount Hamilton, Palo Alto, San Francisco, Ferndale, Fresno, from July 1, 1938, to October 1, 1938, in press.

University of California,
Berkeley, California

PASADENA SEISMOLOGICAL LABORATORY

No written report submitted. See reports and publications of the Laboratory.

NORTHEASTERN SEISMOLOGICAL ASSOCIATION FOR 1939

L. C. Langguth

There are at present nine member stations scattered through New England and in New York State, Pennsylvania, and Canada. The stations comprise Ottawa, with its substations whose readings are available if needed, Pittsburgh, Fordham, Burlington in Vermont, Portland and Machias in Maine, and Harvard, Williamstown, and Weston in Massachusetts. The last-named is the Central Station.

The purpose of the organization is to study both natural and artificial seismic disturbances in the region covered by the network of stations. Seven of the stations operate Benioff vertical seismometers, and of these, two have in addition Benioff horizontal components. The Benioff instruments, because of their ability to write good records of high-frequency vibrations, have proved singularly useful in the study of the local disturbances in which the NESA group is interested.

Readings of all seismic disturbances believed to be of local origin, or in general of all disturbances appearing on the short-period grams and not known to be connected with a teleseism, are sent to the Central Station by post-card. These data are collated at the Central Station, interpreted as local quake, quarry-blast, P-phase of deep-focus shock, etc., as far as possible. Where the data are sufficient, a determination of epicenter and time at origin is made.

In the interpretation of these local disturbances the Harvard Travel Times for New England are used. These were originally compiled from observations made on accurately timed quarry-blasts, and then checked against natural earthquakes. In the checking process it became evident that they might be linearly extrapolated considerably beyond the first limit of about 180 km. Recently Dr. Leet has made available to the NESA Stations a revision of this extrapolation, as far as 1,000 km.

The Association has now been in existence nearly two years and has published its results in a Bulletin issued twice monthly. The Dominion Observatory at Ottawa has generously carried the entire burden of mimeographing and mailing. The issue for the first half of the month of April 1940 will be No. 43.

During the year from April 1, 1939, to April 1, 1940, there appeared in the pages of the Bulletin readings for about 250 different disturbances. Of these, 25 were clearly enough recorded at more than one station to admit of their being identified as dynamite-blasts, and to permit epicenter and time at origin to be determined. Sixteen more were likewise located and verified as natural quakes.

In addition to these routine activities of the Association, the several stations are engaged in special problems with the cooperation of the other members. These include: A study of the ground-motion caused by large blasts, as recorded both by portable instruments and by the permanent installations; the collecting of non-instrumental reports of observed phenomena of natural earthquakes, their analysis, and the construction of isoseismal maps of the area affected,

together with possible conclusions regarding the geology and seismicity of the region; a study of a special type of quake frequently recorded and of epicentral distance about 20°; and work on "rock-bursts," several of which have been recorded on NESA instruments.

Weston College,
Weston, Massachusetts

UNITED STATES COAST AND GEODETIC SURVEY, JANUARY 1, 1939, TO MARCH 31, 1940

F. Neumann

The seismological work of the United States Coast and Geodetic Survey consists principally of three types of activity, namely, teleseismic, strong-motion, and non-instrumental work. The latter deals mostly with information collected from the public and the press.

Teleseismic work--The following is a list of the four Bureau and 21 cooperating and independent stations (three inactive) for which the Bureau is now publishing results. Most of the records are interpreted in Washington (or Philadelphia) and all of the data are adjusted to be consistent with tentative epicenter determinations.

(1) Balboa Heights, Canal Zone (The Panama Canal)
(2) Bermuda (Bermuda Meteorological Station)--A project of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics
(3) Boulder City, Nevada (U. S. Bureau of Reclamation and National Park Service)--Independent project; results not published in monthly bulletin of Survey except in special instances
(4) Bozeman, Montana (Montana State College)
(5) Burlington, Vermont (University of Vermont)
(6) Butte, Montana (Montana School of Mines)
(7) Charlottesville, Virginia (University of Virginia)--Now inactive
(8) Chicago, Illinois (U. S. Weather Bureau and University of Chicago)
(9) College, Alaska (University of Alaska, near Fairbanks)
(10) Columbia, South Carolina (University of South Carolina)
(11) Des Moines, Iowa (Privately operated)--Now inactive
(12) East Machias, Maine (Massachusetts Institute of Technology)
(13) Honolulu, Territory of Hawaii (University of Hawaii)
(14) Huancayo, Peru (Department of Terrestrial Magnetism, Carnegie Institution of Washington)
(15) Ithaca, New York (Cornell University)--Now inactive
(16) Lincoln, Nebraska (Nebraska Wesleyan University)
(17) Logan, Utah (Utah State Agricultural College)
(18) Montezuma, Chile (Smithsonian Institution Solar Observatory)
(19) Philadelphia, Pennsylvania (The Franklin Institute)
(20) Salt Lake City, Utah (University of Utah)
(21) San Juan, Puerto Rico (Coast and Geodetic Survey Magnetic Observatory)
(22) Seattle, Washington (University of Washington)
(23) Sitka, Alaska (Coast and Geodetic Survey Magnetic Observatory)
(24) Tucson, Arizona (Coast and Geodetic Survey Magnetic Observatory)
(25) Ukiah, California (Coast and Geodetic Survey International Latitude Observatory)

In the above group the Coast and Geodetic Survey stations are numbers 21, 23, 24, and 25. Stations operating on a cooperative basis are numbers 2, 3, 4, 6, 8, 9, 10, 13, and 20. Independently operated stations are numbers 1, 5, 7, 11, 12, 14, 15, 16, 17, 18, 19, and 22.

One of the major seismological programs undertaken by this Bureau during the past year, in cooperation with the Bureau of Reclamation is the establishment of a chain of three high-sensitivity seismograph stations in the vicinity of Boulder Dam. The program is well under way under the direction of the Lake Mead Seismological Party. In order to start the operation of the new stations as soon as possible, vibration-meters and suitable recorders have been prepared for use in the new seismograph-vaults until such time as the new seismographs now being built are ready for installation.

A small direct-current motor to operate from a six-volt storage battery and to be controlled by a pendulum-clock has been developed for use at the new Sitka Magnetic Observatory. Tests over a period of several months indicate satisfactory operation. New pendulum-clocks with invar pendulums have been purchased for Sitka and Tucson, for the purpose of improving time-control.

Special time-marks are now being placed on seismograms of most of the stations cooperating with this Bureau. The marks are made by manual operation of the regular time-marking circuit once or twice a day when the radio time-signal is received. Greater confidence in the absolute time of several stations has been established by this procedure.

The second component of the Milne-Shaw seismograph has been sent to Bermuda, and the records from both components are now available for study.

Two McComb-Romberg seismometers loaned by the Franklin Institute were prepared for operation in the Antarctic. Other equipment furnished by this Bureau completed the two-component seismograph for installation near the South Pole. No results have as yet been received from the Antarctic regions.

A smaller, more compact vibration-meter recorder has been developed for use in the California Seismological program.

A serious problem was arising in publishing the data for these stations when, early in 1939, it was found possible to assign about 20 Work Projects Administration workers to the project in the newly established Computing Office of the Bureau at Philadelphia. At that time the publication of results was nearly two years in arrears. At present it is a little more than one year in arrears, and, with increased experience on the part of the personnel (in which there is an unavoidably large turnover) that Office is now producing two to three months' results every month in addition to other miscellaneous work. The results for 1938 are now nearing completion, and as the Washington Office has already done considerable work on the reports for 1939, it is expected that all results will be brought up to date by the close of the calendar year.

One of the accomplishments of the Philadelphia Office was to make a complete set of the normal and deep-focus travel-time curves based on the tables of Gutenberg and Richter. During the past year, seismograms were loaned for special studies to seismologists in Holland and New Zealand and to the seismological stations at Pasadena, Berkeley, St. Louis, Weston, and Pittsburgh in the United States.

Perhaps the most important contribution in the field of teleseismic work was the establishment of a seismographic station at Bermuda through the efforts of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics and the cooperation of the Bermuda Meteorological Station and the United States Coast and Geodetic Survey. Important data bearing on the structure of the Atlantic Basin have already been obtained.

Immediate epicenter-determinations--The cooperative project of the Jesuit Seismological Association, Science Service, and the United States Coast and Geodetic Survey was continued. The Survey distributed cards for 41 earthquakes during 1939 and seven to date in 1940. This work has taken on new significance since the beginning of hostilities in Europe as the International Seismological Association headquarters at Strasbourg was temporarily abandoned and this Science Service project now provides the only immediate and systematic information on the location of important earthquakes.

Strong-motion work--Annual reports on the results of the strong-motion seismograph work of the Bureau on the Pacific Coast and in the western mountain region are published in the Bulletin of the Seismological Society of America. In 1939 no earthquakes of outstanding importance occurred but 18 strong-motion records, covering eight earthquakes, were obtained. Tilt-measurements were made with the cooperation of the University of California, and a large number of building and ground-vibration observations were made. Among the engineering institutions seriously interested and cooperating in this work were California Institute of Technology, Stanford University, and Massachusetts Institute of Technology.

In addition to routine servicing of instruments, instrumental development work was done on high-magnification vibration-meters, a multi-pendulum recorder or "harmonic analyzer" and displacement-meters. In the Washington Office the work of perfecting the double-integration process, whereby acceleration-records are converted to displacement, was continued and is expected to be finished this calendar year. It has been greatly facilitated by the construction of a mechanical enlarging-apparatus which magnifies the horizontal and vertical scales by arbitrary factors. It is expected that many important accelerograph-records now on hand can be processed by this method with the aid of the Philadelphia Computing Office in case that Office is continued into the next fiscal year.

During the year vibration-results were furnished several United States Engineers Offices with reference to the safety of engineering structures, especially dams.

Tiltmeter-observations were continued at Berkeley with the cooperation of the University of California. Seismic acoustic work was also continued but there has been some difficulty in maintaining desirable operating standards.

Non-instrumental work--This consists mostly in the collection of information needed to define the limits of wide-spread shocks and to locate shocks which are too weak to be located by instrumental means and which would otherwise never be catalogued. Active seismological organizations in California cooperate in this program. Most of this work is done on the Pacific Coast and in the western mountain region where special State collaborators aid in the collection of such information. The results are published in San Francisco in mimeographed quarterly reports entitled "Abstracts of earthquake reports for the Pacific Coast and western mountain region." The reports for the second and third quarters of 1939 are now ready for duplication and distribution.

Elsewhere in the United States the work is undertaken by the Jesuit Seismological Association for a specified area in the Central Mississippi River Valley, by the Northeastern Seismological Association for the New England Area and adjoining territory in Canada. The Washington Office of the Survey takes care of the remaining portions of the country. A special preliminary bulletin was issued for the wide-spread southern New Jersey earthquake of November 14, 1939.

The Weather Bureau, through its observers in the field, cooperates actively in this work in all parts of the country.

Miscellaneous--A representative of the Bureau was appointed to a sectional committee of the American Standards Association now drawing up recommendations for building-code requirements for minimum-design loads in buildings. This includes taking earthquake-forces into account.

Mr. Ulrich of the Seismological Field-Survey (San Francisco) compiled a list of earthquake laws in the United States.

The Section of Seismology of the United States Coast and Geodetic Survey worked in close cooperation with the Section of Seismology of the American Geophysical Union in collecting seismological station and instrumental constants for Professor E. Rothé, who is compiling a new list of seismological stations of the world under the auspices of the International Association of Seismology.

The Coast and Geodetic Survey has received a number of records from Rev. J. A. Blatchford, S.J., who now has one component of a Wood-Anderson seismograph in operation at Kingston, Jamaica. This installation was made possible through loan of equipment by the Seismological Laboratory of Georgetown University and by the Pasadena Seismological Laboratory.

Status of seismological publications and reports--During 1939, Part II of "Earthquake history of the United States" covering California and Western Nevada was issued.

"United States earthquakes, 1937" was released in March, 1940. The 1938 annual is expected to go to press in June, 1940.

The quarterly report entitled "Abstracts of earthquake reports for the Pacific Coast and western mountain region" has been issued for the period ending March 31, 1939.

The quarterly "Progress-report on strong-motion work" has been issued for the last quarter of 1939.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF METEOROLOGY

REPORTS AND PAPERS

Washington, D.C.
April 25, 1940

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HUBERT ON THE AFRICAN ORIGIN OF THE HURRICANE OF SEPTEMBER 1938

Charles F. Brooks

The West African origin of the New England hurricane of September 21, 1938, which was suspected by me [see 1 of "References" at end of paper] and probably by others in America and was briefly reported by Henry Hubert as having been the case [2], has now been fully substantiated in a detailed discussion by M. Hubert [3].

The general circulation if West Africa in late summer and early autumn [4] is controlled by the Azores High, the Tamanrasset Low, and the Bouaké High, which is an extension over Guinea and Nigeria of the St. Helena High. Superimposed on these more or less permanent centers are the waves of low and high pressure of an amplitude of about 12 millibars that pass from the east about every four days. In connection with these waves, the circulations of the centers of action may be intensified and extended, bringing diverse air-masses into direct conflict and thereby producing a cyclone.

A westward-moving area of falling pressure that was greater than the usual pressure-wave every third or fourth day made itself felt at Bilma Oasis, at the eastern edge of the French African weather-maps, on September 4. Bilma, in the south central Sahara on the route between Tripoli and Lake Chad, lies in the eastward extension of the semipermanent, heat, low-pressure center of action of the western Sahara, which M. Hubert calls the Tamanrasset Low. The fairly regular westward progress of the September 4 area of falling pressure, and of preceding and following rises and falls is shown on a series of daily isallobaric charts from September 4 to 11 (Fig. 1) and a summarizing diagram. Another set of charts shows the actual isobars, winds, and weather (Fig. 2).

The low-pressure wave in question remained an excrescence on the general low until September 7, when it broke away and became a separate depression with a fairly strong cyclonic circulation about it, some 700 miles in diameter. An incursion of the northerly trade-wind from the Azores High to an exceptionally low latitude on September 7 seems to have initiated the cyclonic circulation, which, by the morning of September 8, involved the southwest monsoon on the south and a dry squall of the easterly equatorial wind on the north.

A heavy, wet line-squall from the east marked the passage of the center over Cape Verde on September 9. The cyclone was centered near the Cape Verde Islands on September 10, and west of them on September 11. On the line of travel and at the speed over Africa the center of the storm on September 13 (Fig. 3) should have been 250 miles south-southwest of the position of the ship that reported strong east-northeast winds shifting to east-southeast in a disturbance on that day [5]. If the track (Fig. 3) the storm followed from September 13 to 18 according to the Weather Bureau [5] is projected backward, the computed position of the storm-center on September 8 comes out only 60 miles from the observed center. If the track according to the meteorologists of Martinique (Fig. 3) is projected backward, the computed position comes to practically the same position as that observed. The isobaric field, with an excrescence of the Azores High projecting southward just ahead of the storm, does not permit of the presence of two cyclones in this general portion of the central Atlantic around September 13. So, in spite of the fact that M. Hubert's and the Martinique track lie appreciably south of the ship-report of September 13, there is good reason for feeling practically certain that the cyclone that left Africa was the same that developed into the hurricane.

M. Hubert thus makes it clear that this and presumably some of the other hurricanes that have come from the Cape Verde Region actually first developed over Africa, and from involvements of two or three air-masses. The West African squalls or "tornadoes" are merely secondary features of the larger whirl wnich is the cyclone.

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[2] H. Hubert, Sur l'origine africaine d'un cyclone tropical dévastateur dans la région de New York, C.-R. des séances de l'Acad. des Sciences, Paris, v. 2^8, p. 456, 1939.

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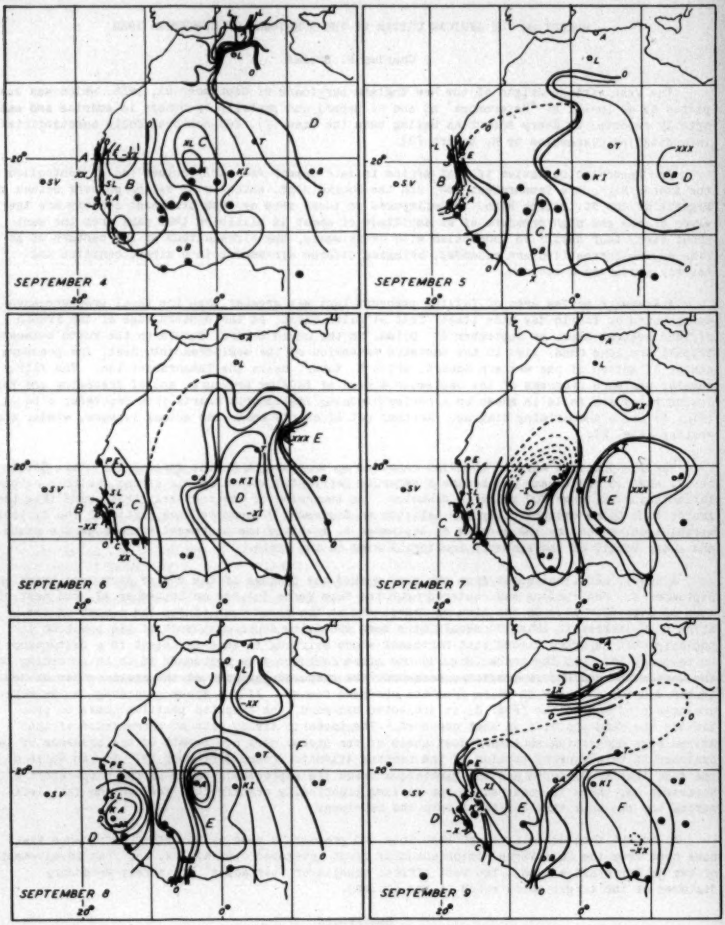

FIG. 1—ISALLOBARS AND RAIN, SEPTEMBER 4-9, 1940

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[6] Charles H. Pierce, The meteorological history of the New England hurricane of September 21, 1938, Mon. Wea. Rev., v. 66, pp. 237-285, 61 figs., 1938.

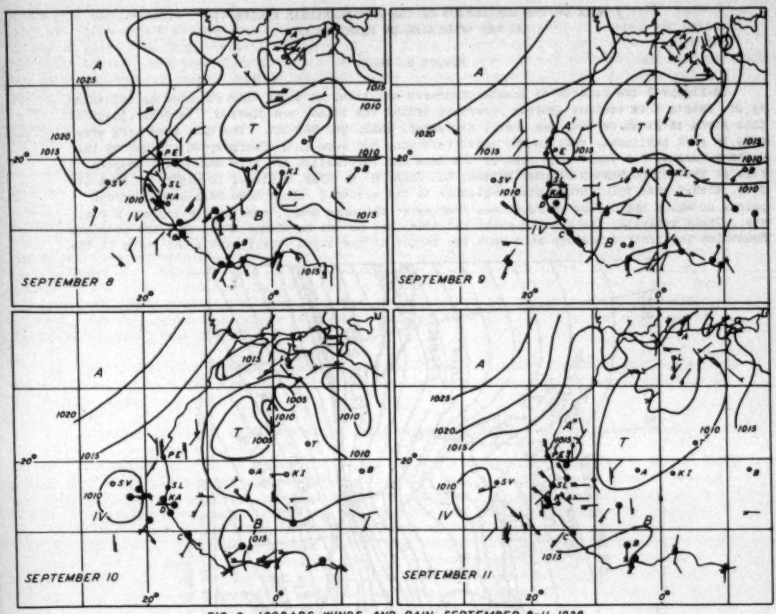

FIG. 2—ISOBARS, WINDS AND RAIN, SEPTEMBER 8-11, 1938

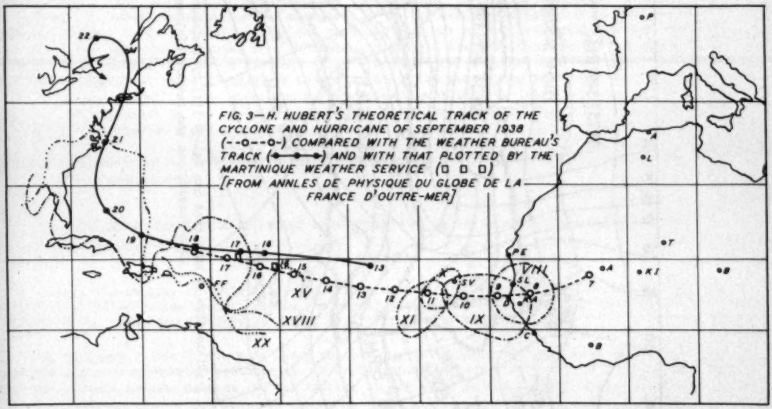

FIG. 3—H. HUBERT'S THEORETICAL TRACK OF THE CYCLONE AND HURRICANE OF SEPTEMBER 1938 (-o--o-) COMPARED WITH THE WEATHER BUREAU'S TRACK (●—●—●) AND WITH THAT PLOTTED BY THE MARTINIQUE WEATHER SERVICE (□ □ □) [FROM ANNLES DE PHYSIQUE DU GLOBE DE LA FRANCE D'OUTRE-MER]

Note: Positions of 1015-mb isobar shown by light broken lines on dates indicated by Roman numerals; Weather Bureau's version of track from September 20 to 22 has been revised by Pierce [6], who places track on 73rd meridian from Cape Hatteras to southern Vermont

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A NOTE ON THE DISTORTION OF THE HURRICANE SAN FELIPE (II) BY THE MOUNTAINS OF PUERTO RICO

Robert G. Stone

In Figure 1 the reports of lowest pressures and times at which they occurred as collected by Dr. Fassig from various amateur observers around the Island are plotted. [A description of this storm is given on Mon. Wea. Rev., September, 1928, pp. 347-352. The data used here were only in part published, some in the above reference and some in a mimeographed account by the Weather Bureau, San Juan. The rest of the data and information are from manuscript sources on file at the United States Weather Bureau, San Juan; R. W. Gray, official in charge of that Office, kindly made this information available to the writer.] Lines have been drawn through points at which the lowest pressure was reached at the same hours, namely, for 1 p.m., 2 p.m., etc. These generally trend north-south but show that as the hurricane moved west the Luquillo Mountains and central Sierras held back the center of the storm locally while the parts of the

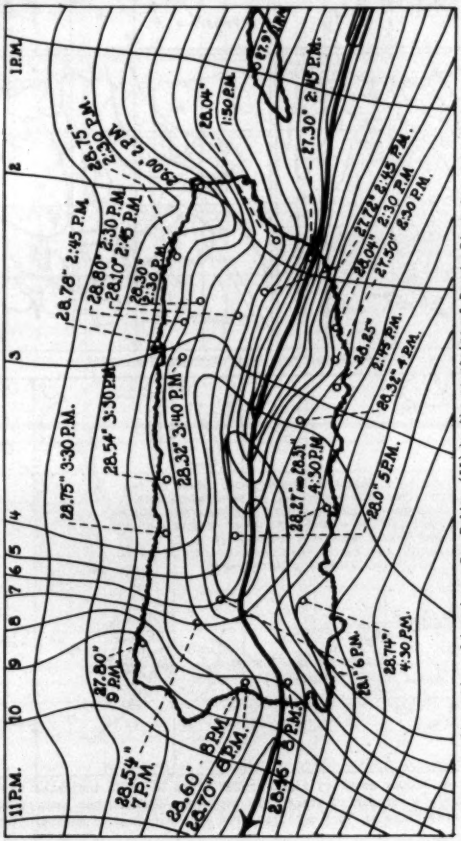

Fig. 1--Distortion of hurricane San Felipe (II) by the mountains of Puerto Rico, September 13, 1928--isochrones and isobars of lowest pressure

storm over the smoother lowlands and over the sea moved on ahead with the usual speed. Then when the storm-center reached the central part of the Island (on September 13, 1928) the delay became so great that even the outlying parts of the storm slowed down for awhile (4 to 10 p.m.) until the center could slowly make its way along the crest of the western mountain and down to the coast. There the normal symmetry was apparently quickly regained (by 10 p.m.) over the smooth ocean, and the center soon (by 11 p.m.) picked up the speed it lost by friction over the rough terrain of the Sierra. Lack of reports from any ship near the coast leaves us only to speculate on the positions of the isochrones over the surrounding waters, but we give what we believe is a reasonable interpretation.

In addition, lines were similarly drawn through points having the same values of lowest pressure; these are not true isobars but merely serve to show the path of the center, which is drawn in a bold arrow. There are two particularly interesting features: First, the slight southward deflection just as the crest of the range in the center of the Island was reached so that thereafter the track ran parallel to the main divide instead of crossing it; and second, the sharp turn southwestward and then northeastward taken by the storm in passing off the mountains back of Mayaguez. The storm thus crossed Mona Passage in a direction quite parallel to that it had before striking Puerto Rico but with its position shifted a few miles farther south. Note also that the Luquillo Mountains caused a great deformation in the isobars of the northwest quadrant, but this distortion hardly altered the general direction of the track since most of the storm was still over the sea.

We have in this case a very interesting example of the well-known effect of mountains in delaying and weakening a hurricane and of its regeneration upon descending the leeward to the sea or lowlands again.

One questionable detail should be noted. The barometer at Isabella (northwest corner of the Island) is reported to have fallen to 27.80 inches; this observation, if it can be relied upon, is the lowest on the west end of the Island and would suggest that the center of the storm passed over that place instead of over Hormigueros, Cabo Rojo, and Mayagüez as drawn. However, the barometers (mostly aneroids) in these cases are admittedly subject to errors which are difficult to ascertain under such circumstances. Since the hour of lowest pressure at Isabella (9 p.m.) seems rather too late compared with the times at surrounding stations, one is led to question the report. Dr. Fassig, however, took these reports at face value and published a map showing the path as passing over Isabella. Reports received some time later, from a ship in Mayagüez harbor and from the log kept by Honorable Jaime Annexy of Hormigueros, leave little doubt that the storm-center passed at least as far south as Mayagüez, if not farther, as we have drawn it. The rather long calm periods observed at Mayagüez and Hormigueros during the passage of the "eye of the storm" would also lead one to doubt that the center passed so far north as Isabella. The track as drawn here is now accepted by the Weather Bureau officials at San Juan and Washington, D. C. However, it is just possible that the calm center when over the west end of the Island was much elongated in a northeast-southwest direction reaching from Isabella to Cabo Rojo or beyond, that is, a distance of 40 miles or more; only the two-hour delay in time of minimum barometer at Isabella leads us to doubt this. The center may even have been split in two by the mountains; or, the mountains may have caused the axis of lowest pressure to lean somewhat to the southwest in the lower levels so that the surface-isobars near the center became elongated as suggested above.

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NEW PROBLEMS AS THE RESULT OF RECENT RADIOSONDE-WORK ON SHIPBOARD IN THE NORTH ATLANTIC

H. W. Rahmlow

Due to the paucity of weather-reports in the North Atlantic as a result of the European conflict, the United States Weather Bureau, in cooperation with the United States Coast Guard, inaugurated the Ocean Weather Service during the first week of February, 1940.

On February 5, the U. S. Coast Guard cutters Duane and Bibb, equipped with the necessary Weather Bureau instruments, proceeded to the designated stations, lying one-third and two-thirds of the distance between Bermuda and the Azores, on the route of the trans-Atlantic clippers.

The daily routine of work on a "floating weather-station" is practically the same as that of an average airport-station. Surface-, pilot-balloon, and radiosonde-observations are taken

Fig. 1--One minute prior to release
[View on quarter-deck of U. S. Coast Guard Cutter Duane during lull in wind; operator making final adjustments on cross-stick launching-device containing about 50 feet of shock-cord which gradually unwinds during flight; small balloon suspended beneath radiosonde contains 400 grams of water and is inflated with sufficient gas to cause it to break near elevation of 15,000 feet, thereby releasing water and increasing ascension-rate]

Fig. 2--Tests being conducted aboard U. S. Coast Guard Cutter Duane
[Shows anchored radiosonde balloon supporting radiosonde which is moved to various positions to test for suitable antenna-location; antenna can be seen just in front and above cotton-region shelter]

daily by the three Weather Bureau representatives on board, and radioed to shore-stations. When planes are in flight, they are kept informed on weather-conditions. Long dashes sent out at intervals from the vessel's radio-transmitters act as a beam for the planes. Each vessel stays on station approximately 21 days, after which period it is relieved by a sister ship.

During the first cruise, which ended March 1, the average hourly wind-velocity was a gale (force 8). The highest observed velocity on the Eastern station (latitude 37° 44' north, longitude 41° 13' west) was 84 miles per hour. Heavy seas were encountered almost daily, with swells estimated up to 70 feet. At times it was necessary to steam six to eight knots to hold the vessel on its position, and even though she was headed directly into the sea, she rolled through an angle of 72°. Only one day occurred with the sea smooth enough to safely launch a life-boat. Intermittent showers and steady rains were frequent, with a strato-cumulus ceiling averaging around 3,000 feet about 80 per cent of the time.

High winds, rough seas, salt spray, and working in surroundings of conductive metals presented the radiosonde-program with a number of new problems.

Due to the unpredictable factors of absorption and radiation of the 4.6-meter wave in surroundings of steel and water, the finding of a suitable location for an antenna becomes a matter of trial and error. A location otherwise suitable may be subjected to shadow-effects caused by the vessel's superstructure. The vessels used in the service are of the light cruiser-type. They are divided into airtight compartments which prohibits the possibility of cutting holes for lead-in cables.

The radiosonde must be protected from salt spray while being exposed. While the surface-check is being made, the radiosonde and its antenna must also be secured if a steady frequency is to be obtained. During periods when there was a considerable difference between water- and air-temperatures, and the wind was gusty, it became somewhat difficult to obtain a uniform temperature-check.

Since none of the hatches was large enough to pass a six-foot balloon, temporary inflation-shelters had to be erected on the quarter-deck. These shelters, though fairly satisfactory for protection against wind, gave no protection against water when the decks were awash.

The greatest problem occurred in releasing balloons during wind-velocities above 35 miles per hour. By having the vessel cruise down wind, it was possible to reduce the apparent wind-velocity by about 15 miles per hour. The ship was maneuvered on a course allowing the use of the longest possible deck-space, and at the same time the wind had to cross the deck at an angle that would prevent the balloon from getting into the down-draft caused by the wind passing over the vessel. When seas were too rough to bring the vessel on the desired course, launchings had to be made without the advantage of the decreased apparent wind-velocity. Launchings were also made when the vessel was under way at a full speed of around 20 knots, while taking one of the crew to the Azores for an emergency operation, and again when she was under way to answer an SOS call from a Greek freighter.

Several men were required to remove the balloon from the inflation-shelter and take it to a position directly up-wind from the observer holding the radiosonde. Balloons were observed to stretch to a length of 18 feet. If the balloon withstood the strain, attempts were made to launch it at the end of a gust on a course that would clear any superstructure and overhead antennas. It was necessary to have the balloon attain an elevation high enough so that the radiosonde would clear any oncoming swells by the time it was released.

In order to have a distance of not less than 30 feet between the radiosonde and balloon during the flight, and still be able to keep the two close together at the time of release, cross-stick launching-devices were tried. They served the purpose, but were impractical due to a large percentage becoming tangled before the cord was completely unwound.

The use of ballast-balloons, though a disadvantage during release, was continued at sea in an effort to cut down the ascensional rates near the surface, which were abnormally high due to the steep temperature lapse-rate. The 400 grams of water which was used in place of the regular sand-ballast caused the ballast-balloons to break more easily when released with a jerk.

The operation of the ground-equipment was also more complicated at sea than on land. Any movement of the antenna-system near the metal of the ship during heavy rolls changed the capacity of the antenna and threw the receiver out of tune. Heavy rolling caused the frequency-meter readings to vary two cycles. In order to avoid irregularities in the recorder-records, the ground-equipment had to be placed in a position so that the operating plane of the recorder-meter was in the plane of the vessel where the least amount of motion occurred. Variations in the visual frequency-meter did not affect the recorder-meter, and were not enough to affect normal operations.

On account of the vibrations and salt, the ground-equipment had to be tested frequently in order to avoid any irregularities. The exposed parts of the antenna, as well as the test-switch, were cleaned of their salt coating occasionally to avoid partial shorts. The vessel's transmitters occasionally caused interference with reception, especially while planes were being contacted.

Until the radio operator becomes accustomed to working on shipboard, he spends over one-half of his time during a flight on his hands and knees, trying to catch his charts and equipment as they scoot around on the deck among the radio equipment.

As the North Atlantic program continues, the radiosonde-records are becoming equal to those produced on land. Better weather-conditions have improved working conditions, but occasional storms still present problems.

The standard cotton-region shelter provides a good protection from salt spray and also a place to secure the radiosonde and antenna while it is exposed to atmospheric conditions. The shelter is used only to obtain uniform conditions to establish a base-line check-record. Surface-observations are taken on the windward wing of the bridge.

The most favorable location for antenna was found to be approximately half-way between the airplane-hoist and the stack at an elevation of sufficient height to extend the dipole above the stack. This position is over the radio room, allowing a short lead-in which can be secured to eliminate any motion to change the capacity. An electric cable is usually removed from a lead-in box extending through the radio-room bulkhead, and the antenna is sealed in its place. In some cases the glass is removed from a port-hole and the lead-in is run through wood and metal discs which replace the glass.

To avoid the sudden jerk and the resulting damage to the radiosonde and ballast-balloon during releases in high winds, a series of heavy rubber bands were used as a part of the shock-cord. A bight was left in the original cord to cover the span of rubber bands, as a protection against breakage.

A temporary framework about ten feet square covered with canvas is used as an inflation-shelter. These shelters are at times damaged by high wind and do not always exclude all air-currents. Permanent structures are being considered with a release funnel in the event permanent weather-vessels are put into service. The release funnel considered will be a steel structure about 15 feet high of sufficient diameter and smoothness to allow an inflated balloon to pass up through it after draft-vents near the bottom have been opened. It will be located on the top of the inflation-shelter and will be closed by a trap-door during the inflation. The top of the funnel will probably have a roll-edge with a venturi arrangement to prevent damage from the shearing effects of air-currents passing across the mouth. The radiosonde will be held on the outside of the funnel until the balloon takes up the slack in the cord.

The Armstrong-type seadrome is also being studied for possible use in obtaining oceanic observations. The ballast- and flotation-tanks are located at a sufficient depth to avoid wave-motion. The deck is located at a sufficient height to allow swells and waves to pass underneath. Small experimental dromes show great stability. If these dromes should prove successful, they would provide the same facilities at sea as an airway land-station without a landing field, at a reduced cost over the use of vessels.

The ship weather-program has brought to attention the need of specially designed equipment for that purpose. New launching devices are being tested, changes in barographs are being made, and improvements in marine theodolites are being considered.

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SOME REMARKS ON THE TECHNIQUE OF PREPARING FIVE-DAY WEATHER-FORECASTS AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

H. C. Willett

Five-day forecasts have been prepared during the past two years at Massachusetts Institute of Technology with the support of Bankhead-Jones funds from the United States Weather Bureau. These forecasts have been aimed primarily at the forecasting of departure from normal of temperature and precipitation for the five-day period, rather than the day-to-day sequence of weather in detail. This was done because it was desired to focus attention on the general large-scale features of the weather situation, on general trends and change of trends, rather than on the details of the minor day-to-day oscillations occurring in any particular locality.

The forecasts are formulated as follows:

For each of three selected regions a forecast of the sign of the expected departure from normal of the temperature and of the precipitation is prepared. Next a forecast of the sign of the change of the mean value of each of these elements since the preceding five-day period is recorded. Thus the forecast for each district consists of four plus or minus signs which are marked right or wrong in accordance with the observed means of these elements in the forecast-period. Finally a numerical estimate of the expected mean temperature and mean precipitation during the coming five-day period is recorded for each forecast-area. These constitute the complete forecast, but the routine verification is based entirely on the 12 plus or minus signs, each of which is checked either as right or wrong according as it agrees or disagrees with the actually observed sign for the area in question.

Each of the districts is verified by the observations of three stations. The northeast section is verified by Albany, New York, and Binghamton, the southeast section by Atlanta, Birmingham, and Chattanooga, and the western section by Wichita, Kansas City, and Springfield, Missouri. The forecasts are prepared on Friday. They are based on weekly mean maps for the week ending Thursday at 7:30 a.m. and daily maps through Friday morning. The forecast begins Saturday morning and runs through Thursday morning, thus covering the last five days of the weekly mean period, and extending seven days ahead of the weekly mean maps on which the forecast is principally based.

The formation of the final forecast is based on the consideration of a number of types of maps and indices. Each of these separate elements is considered in turn, both individually and in conjunction with the others, and they are then combined as harmoniously as possible in the final forecast. An enumeration of these separate forecast-elements, their significance, and general forecast-procedure follows.

(1) The past record--A running graphical record of the averages of temperature and precipitation for the preceding five-day periods in each forecast-district is maintained. This may be used, if desired, for statistical analysis and extrapolation, although such methods are seldom utilized by the synoptic forecasters as offering more than the slightest hint as to the future weather. It will be noted, however, from such a precipitation-record that a forecast of above-normal precipitation stands little better than one chance in three of verification.

(2) The general circulation index--This is defined as the average pressure-difference around the Northern Hemisphere between latitude 35° and 55° north. It gives a rough estimate of the strength of the westerlies on the Northern Hemisphere for the period in question, usually being based on the weekly mean pressure-maps.

The significance of a forecast of this index lies in the fact that the behavior of the principal centers of action, especially the Aleutian Low, is closely connected with variations of this element. Also the general speed of the west-east movement of the daily perturbations (migratory highs and lows) of middle latitudes is more or less directly proportional to the strength of the westerlies, as indicated by the zonal index.

The forecasting of this significant index for the coming week is based in part on a statistical extrapolation of its past behavior, and in part on synoptic indications. The synoptic indications are found in the analysis of the mean surface pressure-maps, especially the individual centers whose integrated behavior is reflected by the zonal index. In other words, the forecast of the zonal index and that of the principal centers of action on the Northern Hemisphere must be adjusted so that they are mutually consistent.

(3) The three-km index--This quantity is determined from the mean three-km pressure-map exactly as the zonal index is determined from the mean surface pressure-map, except that lack of data restricts it to the North American Area. It gives a measure of the westerlies aloft across the United States. This index is probably even more significant than the zonal index as an indicator of the general west-east speed of movement of the migratory centers over North America. When this index is low, at least during the winter half-year, pronounced north-south rather than west-east movement is to be expected. The orientation of this north-south pattern of motion is forecast from the mean three-km pressure-map.

The forecasting of the three-km index, like that of the zonal index, is based in part on statistical extrapolation of its past behavior, but more on the expected appearance of the mean three-km pressure-map itself. The forecast of the three-km index and that of the three-km pressure-map must be mutually consistent, just as must the surface map and the zonal index. Furthermore, the three-km index and pressure-map must be consistent with the surface pressure-map in its larger features. The mutual consistence of these forecast elements must not be lost sight of if it is hoped to combine them all into one rational complete five-day forecast.

(4) The three-km pressure-map--This mean pressure-map is significant principally as the best indicator of stable regimes, or changes of regime, of the general pattern of cyclonic behavior in the United States. It is much better in this respect than the mean surface pressure-map in that it is less disturbed by minor perturbations, giving a much more consistent picture from day to day of the significant features of the circulation in the United States. The poleward gradient on this map gives the three-km index with its indication of general west-east motion, while the distribution of longitudinal gradients indicate the regions of predominant north-south movement of air-mass and cyclone, with the attendant anomalies of temperature and precipitation.

The forecast of the essential features of the three-km pressure-map for the coming week is based in part on the changes of the preceding mean maps, compared with the latest (current morning) daily three-km map, in conjunction with the forecast of the three-km index and the significant features of the surface mean pressure-map.

(5) The surface mean pressure-map (Northern Hemisphere)--This map, by its distribution of pressure-centers, defines the general circulation-pattern, hence the general weather-regime in many localities, during the period which it covers. Therefore, a reasonably correct forecast of

the significant features of this map during the coming week is of fundamental importance to the five-day forecast.

The forecast of the principal features of this map for the coming week is based in part on the preceding mean maps and mean pressure-change maps, in comparison with the latest daily surface-map (current morning) and in part on the forecast of the zonal index and the three-km mean pressure-map, with both of which mutual consistence must be preserved.

(6) The mean isentropic chart--This chart is extremely useful in summer, when the general circulation-pattern becomes so stationary and so little disturbed by migratory disturbances that the cellular units of the circulation-pattern, as shown in the daily isentropic charts, remain clearly defined in the weekly mean maps as well. In winter, on the other hand, much of the time the individual cellular units of the daily isentropic charts suffer so much displacement that the cellular pattern is mostly lost in the weekly mean chart.

The forecast of the mean isentropic chart for the following week is based principally on the mean isentropic maps of the preceding weeks in comparison with the latest daily chart (current morning) and upon significant indications of the surface and three-km mean pressure-maps as to the probable general circulation-pattern.

These six forecast-elements, considered individually and in relation to each other, form the basis of the five-day forecast, which is formulated for each of the three forecast-districts as outlined at the beginning of this discussion.

The forecasts prepared on Friday, April 5, were chosen to illustrate the general method outlined above. It happens that this particular forecast was considerably below average in its verification (about 58 per cent against an average of about 70 per cent) but nevertheless it serves quite well to illustrate the method.

The indications for each of the six forecast-elements mentioned above, as determined from the different maps and charts in accordance with the foregoing discussion, are listed in Table 1.

Table 1--General forecast-elements

(1) Statistical--All temperatures colder, below normal; all precipitation below normal, change - NE + SE and W
(2) General circulation index--Lower
(3) Three-km index--Lower
(4) Three-km pressure--High in west, low St. Lawrence Valley, trough southward along Appalachians
(5) Centers of action--
  (a) High: Hudson Bay, Great Lakes, to East Gulf coast
  (b) Aleutian Low: Weaken, move eastward; also in far west
  (c) Bermuda High: Weak and eastward
  (d) Low-pressure trough just off Atlantic coast, low center over Newfoundland
(6) Isentropic chart--
  (a) Moist tongue from Texas northward (T_G flow)
  (b) Same eastward across the Gulf to Florida and beyond
  (c) Cold, dry dome in eastern United States

Regional forecasts

	Temperature		Precipitation	
	Departure	Change	Departure	Change
NE	-✓	-✓	-✓	-
SE	-	-	+✓	+✓
W	-	-	+	+

The regional forecast for the three selected forecast-districts as determined from the six general forecast-elements are listed in the Table. It is not practicable to try to explain in detail here just how the elements of the regional forecasts follow from the general forecast-elements in this case, although it should be fairly evident to anyone reasonably familiar with weather-map analysis and forecasting in the United States.

The checks indicate five out of the twelve sign-forecasts which failed of verification, a definitely poor forecast. The forecast failed principally as a result of an incorrect estimate of the position of the Aleutian Low and the accompanying anticyclone to the eastward in the

United States. Both of these phenomena were farther west than expected, with the result that the maximum negative temperature-anomaly was found in the central United States instead of in the east, as expected. In the northeast both negative temperature-signs failed, though they verified elsewhere.

This misplacement of the continental high had the further effect of permitting the northeastward advance of warm moist air in the low-pressure trough (frontal zone) on its east side, instead of forcing the moist-air flow eastward along the Gulf Coast to the Atlantic. The result of this was that the two plus signs forecast for the rainfall in the east Gulf section failed, while in the northeast (New York State) the precipitation went above normal instead of remaining below as expected.

An endless amount of detail might be considered in a synoptic discussion of this type, but in the absence of the large number of synoptic charts which are used in the preparation of the above forecast, further discussion of such details is pointless. Only general principles can be treated in a discussion such as the present one, which consequently is terminated herewith in the hope that it has been possible to convey some impression of the general procedure which has been followed at Massachusetts Institute of Technology in the preparation of five-day forecasts.

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CONTRIBUTIONS TO THE THEORY OF THE GENERAL CIRCULATION

C.-G. Rossby

(Abstract)

This paper is a summary of an article now under preparation for the United States Department of Agriculture Yearbook for 1941, in which an attempt is made to present, in non-technical language, a modern picture of the general circulation of the atmosphere. The final model is synthesized through a series of successive steps by means of which the controlling factors are incorporated, one at a time.

It is first shown that on a non-rotating Earth, subjected to uniform insolation, a sharp boundary between troposphere and stratosphere must develop as a result of the convective instability of the vertical temperature-distribution characteristic of radiative equilibrium. In such an atmosphere, only irregular convective circulations develop. Concentration of insolation in equatorial regions leads to development of apurely meridional circulation with a reduction of lapse-rates and suppression of convection in high latitudes.

The effect of the Earth's rotation would at first seem to be the establishment of easterlies next to the ground and westerlies aloft, but further analysis shows that this simple solution is dynamically impossible and that the hemispherical circulation-pattern in a vertical meridional plane must break up into at least three cells, two direct ones (next to the pole and to the equator) and one reverse (in middle latitudes). The mechanics of this circulation is described and the genesis of the polar-front zone is described. The resulting polar front occupies a mean position parallel to the latitude-circles and the mean pressure-distribution at any level is symmetric around the axis of the Earth, as is very nearly the case in the Southern Hemisphere.

It is next shown that if for some reason or other this pattern is being disturbed (by non-symmetric temperature-distributions or by mountain ranges) certain stationary planetary flow-patterns are developed. These patterns may be computed with the aid of the laws for the conservation of vorticity. In the zone of the westerlies these patterns are in the nature of standing waves, the length of which increases with increasing strength of the westerlies. The easterlies poleward of the polar front take on unstable cyclonic paths and must empty into the troughs of the westerlies in a fan-like fashion as a result of subsidence. Thus, the polar front is broken up into separate pieces, extending from southwest to northeast on the Northern Hemisphere. The spacing of these frontal zones increases with increasing strength of the westerlies.

Such a breakdown of the polar front would probably occur also on an Earth of uniform surface-characteristics, but since in that case there would be no preferential injection points of the polar air, the resulting mean pressure-distribution would still be fairly symmetric. In the Northern Hemisphere, however, preferential injection-points are established as a result of the

asymmetric distribution of oceans and continents, and thus the large centers of action are formed.

It is finally shown, through a study of weekly mean pressure-charts, that the dimensions and movements of the centers of action conform fairly well to the theoretically determined flow-pattern characteristics.

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ATMOSPHERIC DISTURBANCES ON THE ROTATING EARTH

B. Haurwitz

In a pressure-field with low pressure to the north, high pressure to the south on which a sinusoidal disturbance is superimposed, more air is transported between consecutive isobars in lower than in higher latitudes. This follows from the geostrophic wind-relation which contains the sine of the latitude in the denominator. Thus, more air flows across the pressure-trough lines than across the wedge-lines. Divergence occurs east of the wedge-lines, convergence to the west and the disturbance moves towards the west provided that the effect of divergence and convergence is greater than the zonal gradient wind-velocity. This effect of the latitudinal variation of the Coriolis force has been studied by Rossby [see 1 of "References at end of paper). He assumes for the sake of simplicity that the lateral extent of the disturbance--that is, its width perpendicular to the direction of motion--is infinite. In reality the width of the disturbance is finite. The effect of convergence and divergence is smaller than in the case of infinite width since the amplitude of the disturbance and consequently the effect of the latitudinal variation of the Coriolis force decrease toward the boundaries of the disturbance and since the isobars are not equidistant any longer. This is borne out by the theory [2]. When wave-length, width of the disturbance, and zonal gradient wind-velocity are in a certain relation to each other, the perturbation is stationary. Figure 1 shows this relation graphically. The ordinate is the width of the disturbance, the abscissa is the zonal wind-velocity. Since the relation depends also on the latitude, three different velocity-scales are given corresponding to latitudes 60°, 45°, and 30°. The curves plotted are lines of equal stationary wave-length. If the wave-lengths were unaffected by the width of the perturbations, the curves would be parallel to the ordinate axis. Especially the curves for longer waves show clearly the effect of the finite width of the disturbances.

When the existence of solenoids generating circulation--which may be found along the coasts of continents--is taken into account, resonance may occur under certain conditions. The perturbations obtain then great intensity. The condition for resonance is that the dimensions of the area over which the solenoidal forces are distributed are the same as the dimensions of the stationary wave-lengths. Figure 1 may therefore also be interpreted as a graph giving the resonance wave-length.

The linear dimensions of the perturbations are so large that it does not seem justifiable to consider the Earth as flat and the latitudinal variation of the Earth's rotation as constant. If these factors are taken into account, the wave-length L at a latitude φ is given by

$$L = (2\pi R \cos \varphi / k) \qquad (1)$$

R is the Earth's radius, k is an integer giving the number of waves around the circumference of the Earth. The expression for the stream function f becomes

$$f = C \cos [(2\pi/T)t + k\lambda] \, P_n^k (\sin \varphi) \qquad (2)$$

C is an arbitrary constant, T is the period, λ is the longitude, P_n^k is an associated Legendre function, n is an integer, and (n - k) indicates the number of nodal parallels of latitude. The velocity c of the perturbation is given by

$$c = \omega R \cos \varphi \, [2/n(n + 1) - \alpha/\omega] \qquad (3)$$

where ω is the angular velocity of the Earth's rotation, α the angular velocity of the zonal motion of the air which is assumed independent of latitude and longitude for the sake of simplicity. Actually the variation of α in temperate latitudes is only small. When $k<4$ the approximations involved in the derivation of equation (3) cause an error, but accurate values can be obtained

from a more complicated formula [3]. The deviations from the case of a flat Earth are quite appreciable.

The perturbations become stationary when

$$\alpha = [2/n(n + 1)]/\omega \qquad (4)$$

This relation represents also the condition for resonance.

In February, for instance, two highs and two lows are found around the circumference of the

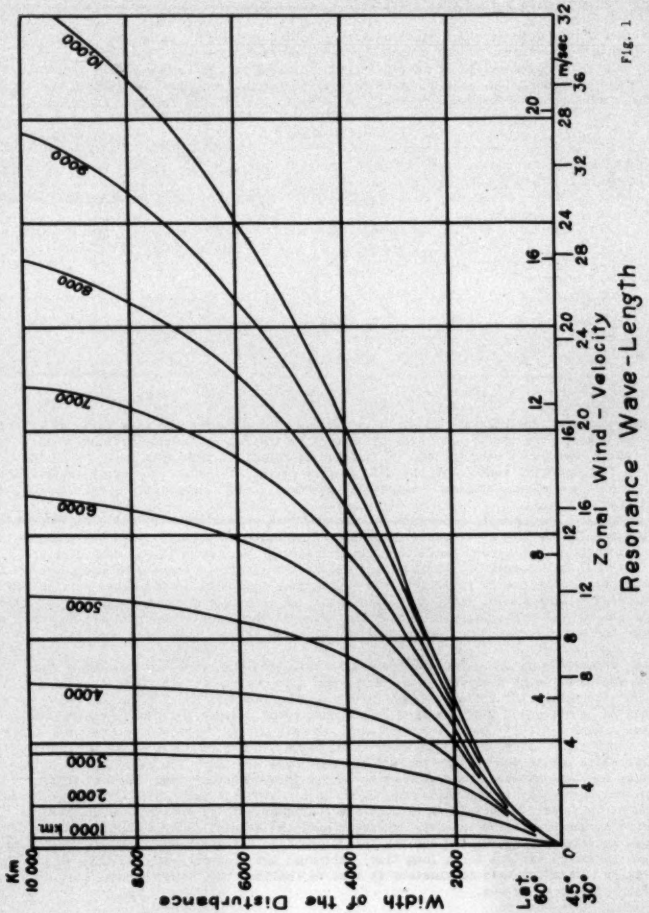

Fig. 1

Earth in temperate latitudes on the Northern Hemisphere, so that $k = 2$. If $n = 5$ it follows from equation (4) that $\alpha = 0.485 \times 10^{-5}$ sec^{-1} while according to observations $\alpha = 0.5 \times 10^{-5}$ sec^{-1}. Thus a perturbation with three nodal parallels could remain stationary. The analysis shows that the nodal parallels are situated at the equator and at about 35° northerly and southerly latitude.

The slower the zonal circulation the larger n must be in the case of stationary perturbations, according to (4). Larger n implies smaller perturbations. Now, the intensity of the zonal circulation depends on the meridional pressure-gradient. Allen [4] has shown that actually the pressure-distribution appears broken up into smaller cells the smaller the meridional pressure-gradient which agrees with the preceding conclusions.

In view of the unsymmetrical distribution of water and land it is not to be expected that the large-scale circulation of the atmosphere can ever be represented by a single spherical harmonic but rather by a series of harmonics, in a similar manner as the yearly temperature-period can be represented by a trigonometric series. In such a series the terms closest to the possible free harmonics determined by equation (4) will predominate owing to resonance.

References

[1] C.-G. Rossby, J. Marine Res., v. 2, p. 38, 1939.
[2] B. Haurwitz, J. Marine Res., v. 3, p. 35, 1940.
[3] B. Haurwitz, Beitr. Geophysik, v. 51, p. 195, 1937. [Equation (50) in which the influence of α has to be considered.]
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COMPARISON OF OBSERVED AND COMPUTED OUTGOING RADIATION-INTENSITIES

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(Abstract)

When clear-weather outgoing radiation-intensities for a number of polar stations are plotted against temperature (of the air near the observing instrument) a wide scatter of points is found in which, however, there is seen an increase in radiation-intensity with increasing temperature. The principal reason for the wide scatter is that for a given surface-temperature the variations of the vertical temperature and moisture-distribution, particularly the former, may be quite large.

The variation in the magnitude of the surface-inversion is usually the most important factor--a low value of outgoing radiation-intensity occurring during large inversions and vice versa. This relation becomes clear when one realizes that since the outgoing radiation is the difference between the upward radiation from the surface (black-body radiation) and the downward radiation from the atmosphere (non-black-body radiation), then for the same atmospheric radiation the lower the surface-temperature the lower the outgoing radiation-intensity, or, in other words, the larger the surface-inversion the smaller the outgoing radiation-value.

Quite remarkable is the difference in radiation-intensities (for a given temperature) between two groups of polar stations, A and B. Group A is composed of Mt. Nordenskiöld, Spitsbergen (78° 11' north, 15° 26' east, 1,049 meters), and Calm Bay, Franz Josef Land (80° 19' north, 52° 48' east, about 1,300 km from Mt. Nordenskiöld). Group B includes the following: Fairbanks, Alaska (65° 51' north, 147° 52' west, 135 meters), Ft. Smith, Northwest Territory (60° 00' north, 111° 53' west, 210 meters), S. S. "Maud" (northern coast of Eastern Siberia), and Fargo, North Dakota (46° 54' north, 96° 48' west, 274 meters). The outgoing radiation-intensities for the stations in Group A agree well with one another, and the same is true for those in Group B but the former values are about double those of the latter. The aerological data suggest that smaller surface-inversions are characteristic of the Group A atmospheres, which leads to the conclusion that air of recent maritime origin, such as that over Group A, cools more rapidly and has smaller surface-inversions than air which has been over continental (or frozen maritime) regions for a long time. Although the proximity of Fairbanks to the ocean might seem to contradict this conclusion, it must be realized that large mountain barriers shield Fairbanks from the sea.

An attempt was made to compare the observed outgoing radiation-intensities with those computed by means of the recent Elsasser diagram, which involves use of the vertical soundings of temperature and humidity. Simultaneous radiation and aerological observations to an appreciable height were made only at Fairbanks and Fargo, and only those observations were used when two or more closely agreeing clear-weather radiation-measurements were made within a few hours of an aerological sounding. The results showed that for the two stations the computed values of the outgoing radiation were about 50 per cent larger than those observed, and, furthermore, even when 100 per cent relative humidity was assumed throughout for each sounding the computed values were still about 13 per cent too large. Possible factors accounting for this difference, such as (a) instrumental and observational errors, (b) errors in the construction of the diagram, (c) effect of other radiating gases such as carbon dioxide and ozone, and (d) effect of solid particles present in the atmosphere, were examined and no definite conclusion was reached.

The complete report of this work will be published in a forthcoming issue of the Monthly Weather Review Supplement.

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Washington, D. C.

FURTHER REMARKS UPON THE INFLUENCE OF ALTITUDE ON THE ANNUAL COURSE OF AIR-PRESSURE

V. Conrad

In an earlier paper [see 1 of "References" at end of paper] the influence of altitude on the annual course of air-pressure was examined. The annual and semiannual waves were considered. It was shown that the annual wave is a thermal wave, the amplitude of which increases with altitude above sea-level in a strictly linear way. The semiannual wave resulted as a pressure-wave and seems to be a forced wave because the amplitude is invariant with altitude. It was stated that the Fourier series which represents the annual variation did not converge well, so that it was necessary to consider also the third wave.

The attempt made in this note uses the observations of 33 places in the European Alps. The pressure-data were taken from a paper of J. von Hann [2] and from the "World weather records" edited by H. Helm Clayton. The material is nearly the same as in the earlier paper.

To save space, Table 1 contains only the numbers of stations because the names are of no interest to the American reader. a_3 and A_3 indicate the amplitude and the phase-angle of the

Table 1--Results of harmonic analyses of variations of air-pressure at 33 stations in the European Alps

Station No.*	Elevation above sea-level	Calculated				Station No.*	Elevation above sea-level	Calculated			
		a_3	Δa_3	A_3	ΔA_3			a_3	Δa_3	A_3	ΔA_3
	meters	mb	mb	°	°		meters	mb	mb	°	°
1	26	0.76	-0.09	74.9	+ 4.8	18	742	0.84	-0.01	72.8	+ 2.7
2	42	0.92	+0.07	73.1	+ 3.1	19	769	0.76	-0.09	74.7	+ 4.6
3	67	0.45	-0.40	75.2	+ 5.1	20	797	0.89	+0.04	72.0	+ 1.9
4	162	1.12	+0.27	66.5	- 3.6	21	812	1.10	+0.25	68.4	- 1.7
5	202	0.74	-0.11	67.7	- 2.4	22	910	0.74	-0.11	57.3	-12.8
6	264	0.81	-0.04	69.2	- 0.9	23	994	0.70	-0.15	64.8	- 5.3
7	299	0.89	+0.04	70.7	+ 0.6	24	1023	0.64	-0.21	53.5	-16.6
8	356	0.98	+0.13	70.1	- 0.0	25	1044	0.89	+0.04	71.9	+ 1.8
9	390	0.77	-0.08	87.0	+16.9	26	1335	1.14	+0.29	74.1	+ 4.0
10	436	0.98	+0.13	70.4	+ 0.3	27	1776	0.98	+0.13	73.8	+ 3.7
11	467	0.76	-0.09	69.1	- 1.0	28	1811	0.77	-0.08	59.0	-11.1
12	468	0.72	-0.13	71.8	+ 1.7	29	2044	0.69	-0.16	59.4	-10.7
13	489	0.88	+0.03	69.4	- 0.7	30	2476	0.82	-0.03	70.4	+ 0.3
14	550	0.93	+0.08	69.5	- 0.6	31	2500	0.53	-0.32	67.8	- 2.3
15	553	0.80	-0.05	72.1	+ 2.0	32	2962	1.29	+0.44	83.1	+13.0
16	668	1.37	+0.52	71.3	+ 1.2	33	3106	0.74	-0.11	71.0	+ 0.9
17	673	0.81	-0.04	71.5	+ 1.4						

* For names of stations see reference [1].

third Fourier term of the form $a_3 \sin(A_3 + 3x)$, where $x = 30°$. The arithmetical means are $\bar{a}_3 = 0.857$ mb and $\bar{A}_3 = 70°.1$; Δa_3 and ΔA_3 are the deviations of the above average values.

As it is to be seen from Table 1, the numbers of the stations are arranged according to increasing altitude. If there were a strong influence of elevation above sea-level on the values a_3 and A_3, it should be apparent by inspection of Table 1; evidently there is no such influence. The possibility of a weak influence remains, however.

Applying the probability-criterion of Helmert, we have $(c - s) = +4$ for the series of a_3 and $(c - s) = +4$ for the series of A_3. If c is the number of changes of the signs and s is the number of sequences of the signs, Helmert's criterion states that

$$(c - s) = 0 \pm \sqrt{n - 1}$$

if n equals the number of elements of the series and there is an arrangement of the elements only at random. The standard deviation $F = \pm \sqrt{n - 1} = \pm 5.7$ for $n = 33$. Thus the difference $(c - s)$ lies within the limits given by $0 \pm F$.

Abbe's criterion was also considered. For deviations ϵ_i and $Q = \sum_{\epsilon_i=1}^{\epsilon_i=n} \epsilon_i^2$ and $R = \sum_{\epsilon_i=1}^{\epsilon_i=n} (\epsilon_i - \epsilon_{i+1})^2$ we have $(2Q/R) = 1 \pm \sqrt{1/n}$, that is (1 ± the standard deviation), if there is an arrangement of the numbers at random. The standard deviation is $\sqrt{1/n} = \pm 0.174$ in the two cases, so that the ratio $(2Q/R)$ must be between 0.826 and 1.174 if no systematical influence exists on the numbers arranged according to altitude.

For a_3, $(2Q/R) = 0.766$, and for A_3, $(2Q/R) = 1.216$. In these two cases the critical ratio lies beyond the limits given by the standard deviation. But the differences between the resulting values and the lower or the upper limit are so small that there is no urgent reason to assume that a systematic influence of altitude is probable either on a_3 or on A_3.

If the deviations from $\bar{a}_3$ as well as from $\bar{A}_3$ are to be considered as accidental errors, then the standard deviations are ± 0.2 mb for a_3 and ± 6°.4 for A_3. The two standard deviations are small; that of A_3 is nearly negligible, if we consider that here 6° corresponds to about two days only.

It follows that a_3 as well as A_3 are in all probability invariant with altitude. Therefore, the third wave does not change with altitude. It is clear that this term of the annual variation of pressure is caused somehow by dynamic factors and not by either thermal factors or by oscillations of the atmosphere.

The result is surely of interest but an important question remains: Does the third term have any physical meaning if the Fourier series converges badly? To test this, the annual variation for station 25 (Table 1) was calculated as an example at random. The results are given in Table 2.

Table 2--Results of harmonic analysis of annual variation of air-pressure at Station No. 25 of Table 1

Month	Obs'd Δ p	Calculated Fourier terms				(Obs'd - calculated)
		First (I)	Second (II)	Third (III)	(I + II + III)	
	mb	mb	mb	mb	mb	mb
Jan.	-0.49	-2.26	+1.01	+0.84	-0.41	-0.08
Feb.	-1.80	-2.81	+0.78	+0.28	-1.74	-0.06
March	-3.92	-2.59	-0.24	-0.84	-3.67	-0.25
April	-2.41	-1.69	-1.01	-0.28	-2.98	+0.57
May	-0.86	-0.33	-0.78	+0.84	-0.28	-0.59
June	+1.77	+1.10	+0.24	+0.28	+1.62	+0.15
July	+2.78	+2.26	+1.01	-0.84	+2.43	+0.35
Aug.	+2.79	+2.81	+0.78	-0.28	+3.31	-0.52
Sep.	+3.39	+2.59	-0.24	+0.84	+3.19	+0.20
Oct.	+1.29	+1.69	-1.01	+0.28	+0.96	+0.33
Nov.	-1.86	+0.33	-0.78	-0.84	-1.29	-0.57
Dec.	-0.77	-1.10	+0.24	-0.28	-1.14	+0.37

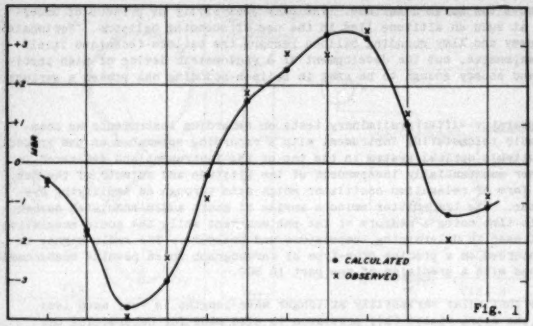

Fig. 1

The last column of Table 2 is of interest. Abbe's criterion for this series is (2Q/R) = 0.607 and the limits given by the standard deviation are 0.711 and 1.289. Therefore, while not necessarily so, it is probable that the residuals contain further periodical terms. On the other hand, Figure 1 shows that the three terms give a curve which fits well with that for the observed values.

It is to be emphasized, however, that the second and the third terms show a very well-determined behavior with altitude. The results of the observations make it difficult to question the invariance with altitude of a_2, a_3, and A_3. It is improbable that this invariance would hold in so many cases if the two terms had no geophysical significance. Therefore, a closer discussion of the meaning of the two terms would be necessary. They are--as we have said--surely not caused by thermal factors or by oscillations of the atmosphere. They are thus produced by periodical convergences and divergences of air-masses. Doubtless these transports of air are intimately connected with the general circulation. It would be not only of interest to make further examination of the average behavior of these terms but also of their temporal variations.

References

[1] V. Conrad, Bull. Amer. Met. Soc., v. 20, pp. 207-209, 1939 (on p. 208, right column, fifth line from the bottom, read "static equation" instead of "hydrostatic equation"); see also Met. Zs., v. 55, pp. 429-435, 1938.

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PROGRESS-REPORT ON DEVELOPMENT OF A PROCEDURE FOR THE STUDY OF SOLAR VARIABILITY BY ULTRA-VIOLET MEASUREMENTS IN THE STRATOSPHERE

Brian O'Brien, H. S. Stewart, Jr., L. T. Steadman, and H. W. French, Jr.

The importance of determining the magnitude and character of any variability which the Sun may exhibit justifies additional study of fluctuations in the intensity of solar radiation as received at the outside of the Earth's atmosphere. Such a study was undertaken by the Institute of Optics of the University of Rochester three years ago with the financial aid of the Smithsonian Institution. Because of the very considerable experimental difficulties involved, our work up to the present has been devoted to the development of apparatus and procedure.

There is evidence that the principal variation in the output of radiation from the Sun occurs in the ultra-violet region of the spectrum [see 1 of "References" at end of paper], and that enough of this variation may occur in regions of the ultra-violet which are transmitted by the Earth's atmosphere to make its detection possible by suitable measuring instruments suitably located. Unfortunately errors introduced by uncertainties in the transmission of the Earth's atmosphere are greatest in the ultra-violet, so that measurements of this spectral region from the Earth's surface are not yet of proven value [2].

An obvious way to avoid the greater part of atmospheric uncertainties is to place the measuring instrument at a point in the Earth's atmosphere above the regions of known contaminations such as dust, water-droplets, and ice-crystals. This appears to require altitudes of at least

15 km and better of 20 km above the Earth's surface. The only possibility at present of undertaking routine measurements at such an altitude lies in the use of sounding balloons. Fortunately the development of the Dewey and Almy sounding balloon renders the balloon-technique itself comparatively simple and inexpensive, but the development of a radiometric device of high precision which is light enough and sturdy enough to be used in balloon-sounding has proven a serious problem.

Basic arrangement of apparatus--After preliminary tests on recording instruments we abandoned these in favor of a radio telemetering instrument with a recording apparatus on the ground. Sunlight is received by a suitable optical system in the top of the instrument and delivered to a vacuum-photocell in a manner substantially independent of the altitude and azimuth of the Sun. The photocurrent actuates a form of relaxation-oscillator which acts through an amplifying system to key a radio transmitter. The transmitter emits a series of short audio-modulated dashes, the number of dashes per unit-time being a measure of the photocurrent while the audio-modulation provides an accessory signal used in determining temperature and pressure. The radio signal as received at the ground is recorded on a precise drum-type of chronograph which permits measurement of the interval between dashes with a precision of one part in 500.

Because of the evidence that solar variability at longer wave-lengths is very much less than any which may exist in the ultra-violet [1], provision is also made for determining the radiation-intensity in the infrared just beyond the visible spectrum. Because measurements in this region of the spectrum where the atmosphere is very transparent can be carried out successfully from the ground, a control is thus provided of the performance of the balloon instrument. If the balloon instrument indicates any substantial daily fluctuations of solar intensity in the near infrared this will serve as a warning that some part of the measuring equipment is functioning improperly.

The optical system--The ultra-violet and infrared wave-length regions used have been selected with reference to the known absorbing gases in the atmosphere. The ultra-violet filters transmit a region centering about 3,600 Å, the short wave-length end of which terminates before any substantial ozone-absorption occurs. The infrared filters transmit a region centering at about 8,000 Å and terminating at the long wave-length end before reaching any important water-vapor absorption-bands.

The ideal optical system is one which delivers to the photocell an amount of radiation which is proportional only to the intensity received by a unit-area normal to the solar beam, and independent of the altitude or azimuth of the Sun with reference to the instrument. The system now in use consists of a sphere of opal glass, transmission-characteristics of which are nearly independent of wave-length over the entire spectral region used and are sufficiently independent of temperature from +30° to -60° C. The distribution of thickness of the glass in the opal sphere is such that the above condition of independence of altitude and azimuth is nearly achieved. Each diffusing sphere, rigidly mounted with its photocells, is given final adjustment by masking lacquer until the system is independent of azimuth and independent of altitude-angle over a wider range of this angle than encountered in flight. The photometric precision in the adjustment of these spheres is carried to about one part in 500.

For reasons which are described under "Photocells," it is desirable that a single sphere serve for both the ultra-violet and infrared. Our present technique consists in using a carbon-black masking lacquer for the infrared adjustment and a yellow-dye lacquer for the ultra-violet adjustment. The yellow dye has been selected to be very transparent for the infrared and very opaque for the ultra-violet.

Photocells--Caesium-oxygen-silver vacuum-photocells are used for both ultra-violet and infrared. A careful study of fatigue, stability, and temperature-coefficients of these cells indicates that it is better to illuminate a single cell continuously with one spectral region than to alternately illuminate a cell with ultra-violet and infrared. Two photoelectric cells are therefore so mounted as to receive light from the same optical system, as shown in Figure 1. Fresnel reflection from the clear, ultra-violet, transmitting diagonal glass-plate P illuminates the cell C_1, provided with an infrared transmitting filter, while the light transmitted by the plate P illuminates the cell C_2, provided with an ultra-violet transmitting filter. Glass filter-combinations which have been investigated for stability and temperature-coefficients are used for both spectral regions.

It has not been possible to secure photocells which are free from either "fatigue" or temperature-coefficient effects. Moreover, the "fatigue" is a function of applied voltage on the photocell. Temperature-effects are eliminated by temperature-compensating each photocell

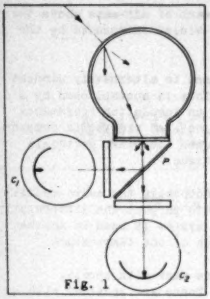

Fig. 1

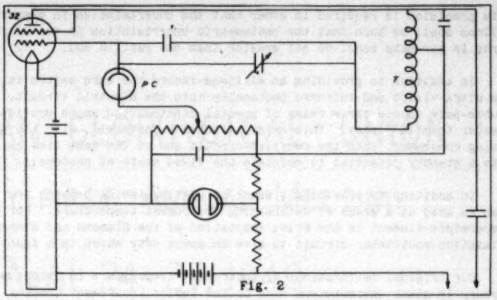

Fig. 2

with its associated electric circuit as described under "Circuits." "Fatigue" is maintained at a substantially constant level by providing the cells with continuous illumination during flight and with a constant value of applied potential for some hours preceding and during a flight.

An unexpected difficulty was encountered in the influence of the Earth's magnetic field on the apparent sensitivity of a photocell. This field in the vicinity of Rochester is slightly more than 0.6 gauss, but is sufficient to introduce errors of as much as two per cent when the orientation of the photocell with respect to it is changed. The effect of the field appears to be due to a deviation of electrons away from the collecting anode with a consequent building up of large space-charges on the tube-walls. The effect of the Earth's magnetic field is reduced by the use of magnetic shields around the photocells to a point where the uncertainty in photometric measurement resulting from it is not greater than one part in 400.

Circuits--The basic circuit used for converting photocurrent to electrical pulses is a form of relaxation-oscillator shown in Figure 2. With the photocurrents and circuit-constants which we use, no plate-current flows except in the form of sharp pulses lasting about 1/1000 second. The negative charge on the control-grid leaks off as photocurrent until the negative bias of the grid diminishes to a point where plate-current begins. A sharp pulse of plate-current follows, and the grid is again left with a strong negative charge. Since considerable amplification occurs in this form of relaxation-oscillator we have termed it for convenience a "recycling" amplifier. This circuit has been very carefully investigated for stability, for the influence of plate- and filament-potentials upon it, for electrical pickup or feed-back from other parts of the electric system such as the radio transmitter, and for temperature-effects. The latter are present due both to phenomena within the vacuum-tube and to the iron-core audio-transformer T. The transformer introduces a temperature-effect due to the change with temperature of the dielectric constant of the materials with which the transformer-windings are insulated, since the distributed capacity of the transformer-windings plays a part in the circuit. Fortunately we have been able to find a semi-solid petroleum-product which is a good insulator and which possesses a large temperature-coefficient of dielectric constant in the reverse direction of that exhibited by commercial-transformer insulation. Suitable vacuum-impregnation of the transformer-windings thus accomplishes nearly complete temperature-compensation of this "recycler"-circuit. The final temperature-compensation of the circuit with its associated photocell is accomplished by a very small air-condenser of about 5-$\mu\mu$f capacity which is in parallel with the grid-blocking condenser and which is actuated by a bimetallic strip.

The pulse-rate in the recycler-circuit is a linear function of the photocurrent over a wide range, but is also a function of the applied plate-voltage. The plate-voltage is stabilized to better than one part in 500 by a miniature gas-discharge voltage-regulator mounted in a small Dewer flask and continuously operating at a battery-drain of about 0.8 milliampere.

Pressure and temperature-elements and switching--On test-flights the position of a balloon in space is continuously determined by a triangulation-technique previously described [3]. However, to render the system independent of visibility for routine flights a barometric element is also used. This is a modification of the barometric switch used in the Diamond and Hinman radiosonde [4] system as manufactured by Julien P. Friez and Sons. The switching sequence of the standard Friez instrument is altered and the barometric capsule-stroke is doubled to reduce the error in measurement of barometric pressure to less than two mm of mercury under all conditions.

This precision is required in order that the uncertainties in measurement of air-mass above the balloon shall be such that the photometric uncertainties in the ultra-violet introduced by the error in air-mass shall be not greater than one part in 500.

In addition to providing an altitude-record the baro switch is used to alternately connect the ultra-violet and infrared photocells into the electric circuit. This is accomplished by a double-pole double-throw relay of special construction which provides an insulation-resistance greater than 10^{14} ohms. This relay switches a photocell, with its associated bimetallic compensating condenser, into the recycler-circuit and at the same time switches the other photocell onto a standby potential to maintain the fixed state of photocell-"fatigue."

In addition to providing a means of distinguishing between two photocells the audio-modulation is used as a means of determining instrument-temperature. For this purpose the electrolytic temperature-element in the Friez adaptation of the Diamond and Hinman system is used in another relaxation-oscillator circuit to give an audio note which is a function of the temperature.

Our original calibrations of instrument-temperature in flight were made with special mercury-in-glass thermometers made by the Taylor Instrument Company. These are provided with a silver coating on the outside of the capillary and with an electrical lead-wire in the mercury bulb, thus forming a variable condenser which replaces the grid-blocking condenser of the recycling circuit. For such temperature-tests and for studies of the performances of the electric circuits independent of the photocells, the latter were replaced by a sealed glass ionization-chamber provided with a sufficient quantity of polonium to give an ionization-current of the same order as the photocurrents (5 10^{-10} ampere). By a suitable mixture of gases sealed in the ionization-chamber the temperature-coefficient of recombination is rendered substantially zero, so that the radioactive grid-leak thus provided yields a current independent of voltage and independent of temperature from +30° to -40° within about one part in 400.

The radio transmitter consists of a conventional push-pull circuit using two type-30 tubes. This transmitter is grid-keyed by the recycler-circuit through a buffer-and-amplifier circuit which introduces a time-delay for the conversion of the sharp pulses into dashes of about 0.1-second duration.

Receiving and recording system--The selection of the receiver-circuits has been influenced by the necessity of using a receiver-location where considerable unfavorable interference occurs. Two superheterodynes in series are used with the first intermediate frequency ten megacycles and with variable band-pass in the second intermediate-frequency stage. (We are indebted to the Stromberg-Carlson Telephone Manufacturing Company for valuable assistance in connection with the radio-receiver problem.) The receiver is provided with a noise-rectifier and the receiving antenna consists of a five-element directional array of vertical doublets.

Radiation-standards--The maintenance of laboratory-standards of radiation for calibration of each instrument before flight is a separate problem which will not be discussed in detail here. It appears that with care we shall be able to maintain such a standard to a precision of about one part in 500 in keeping with the goal which we have set in the development of the rest of the apparatus.

Results--Some 30 flights have been made for the purpose of testing and calibrating various portions of the apparatus. As a result of these it appears that we can probably depend upon radiometric measurements in the stratosphere in two wave-length regions to within about one part in 200. Our goal in laboratory-performance has been one part in 500, but in spite of every precaution we have not yet approached this in actual flight. For the purpose of our present study of solar variability it seems probable that a precision of one part in 100 may be adequate, and there seems to be little doubt that our apparatus has now surpassed this. We hope, therefore, to undertake routine measurements on something like a weekly basis in the near future with flights to an altitude of 20 km.

Further details of apparatus and circuits will be reported in another place.

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

REPORTS AND PAPERS

Washington, D.C.

April 24, 1940

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SOME FEATURES OF THE LARGE GEOMAGNETIC TIDES IN THE HORIZONTAL FORCE AT HUANCAYO

J. Bartels and H. F. Johnston

(1) Introduction--The effects of the lunar tide-producing force, so clearly recognizable day by day in the oceanic tides, are veiled in the lower atmosphere by much larger non-tidal movements. Nevertheless, long series of barometric readings have yielded accurate information about the lunar atmospheric tides. Lunar variations have also been found in the geomagnetic force components; they may be called "geomagnetic tides" since these lunar daily magnetic variations L have been linked by the dynamo-theory with tidal motions in the ionosphere. They are the result of a comparatively simple large-scale experiment which is performed daily by the Moon on the Earth and which, involving only gravitational forces, is more easily interpreted than the solar daily variations S, in which magnetic effects of the tidal forces are rather inextricably mixed with those produced by simultaneous daily changes in solar-heat radiation and ionizing power. The study of L yields information about the lunar tidal motions as well as about the changes of total ionization in the ionosphere.

For a number of observatories, data on L have been extracted from many hourly values. An account of the results is given in two recent treatises [see 1 and 2 of "References" at end of paper]. The daily range of L--that is, the difference between the highest and lowest values--was found to be small in all cases of the order of a few γ and, in the general average, about ten per cent of the daily range of S in the same material. It was therefore surprising to find a case where L, so to speak, luxuriates. At the Huancayo (Peru) Magnetic Observatory of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, L in the horizontal force H is so large relative to S that the form of the daily recorded curves (S+L) on the magnetogram is shaped by L, thus changing with the Moon's phase. Since, furthermore, S in H at Huancayo is by far the largest observed anywhere on the Earth, reaching daily ranges of over 200γ at sunspot-maximum, L is also large in absolute units; at sunspot-maximum in January the daily range in L is greater than 60γ, considerably surpassing the daily range of S at many stations.

Throughout this paper--except in section 9--only undisturbed days will be considered, more exactly, all days with international character-figures C under 1.2, since preliminary studies had shown that S and L at Huancayo are not systematically affected when C increases from 0.0 to 1.1. Therefore, S means S_q in Chapman's notation [1]. L is greatest around January; part of the more detailed discussion is therefore restricted to this time of the year.

(2) The average lunar and solar daily variations in January--Figure 1 combines the main results on S and L in H at Huancayo for the month of January, 1922-39. The upper half of Figure 1 refers to sunspot-minimum, the lower half to sunspot-maximum; the solar activity is indicated at the left by two spectroheliograms taken at Mount Wilson Observatory in calcium light (Fraunhofer K-line). The two frieze-like diagrams at the upper and lower borders are derived from all observations on undisturbed days and show the systematic superposition of S (second row) and L (third row) to form the observed daily variation (S+L) in the first row; they are schematic in so far as they represent the average S- and L-variations as if they were completely determined by the season (here, month of January), the sunspot-number, and in the case of L, by the phase of the Moon; actually there are additional fluctuations from day to day, to be considered later (section 3).

All calculations are based on the mean Moon which completes a synodic month from new Moon to new Moon in 29.53 solar days (intervals between successive midnights) or 28.53 lunar days (intervals between successive lower transits of the Moon). The "Geophysikalische Mond-Tafeln" [3] were used. For each day at Greenwich noon the age ν of the mean Moon is defined as the angle between the Earth's meridian planes through the mean Sun and the mean Moon, increasing from 0° to 360°, or 0 hour to 24 hours of 15° each, between successive new Moons. The "Tafeln" tabulate a quantity μ from which $\nu = (24 - \mu)$ is immediately obtained to the nearest hour. In Figure 1 small schematic pictures indicate the Moon's phases for ν = 0 hour, 1 hour, 2 hours, etc. The ordinate-scale is indicated by the vertical lines at the right which give 296γ, one per cent of the average horizontal force H at Huancayo.

S, L, and (S+L) are pictured as departures from the night level because the main swing of the curves is confined to the daytime (section 13); day and night are roughly separated by vertical lines drawn at 06^h and 18^h. L can be described as a lunar semidiurnal wave with maxima about seven hours after the Moon's transits; this wave appears only in the daytime and is suppressed at night. The tidal cause of L is evident in the similarity of the curves for the two halves of the synodic month demonstrating once more that not the light of the Moon causes L, but

its semidiurnal tidal forces, for which upper and lower transits are equivalent.

(3) Cases of exceptionally large lunar influences--Actually the daily variations vary not only systematically as pictured in the two friezes, but also in a less regular manner from day to day. This is a well-known property of S, although some of the "variability" formerly ascribed to S is actually the result of the superposed L-variation which had been underestimated. The large magnitude of L in Huancayo H affords for the first time the opportunity to detect striking changes in the amplitude of L from day to day. Compared with the average curves obtained from many observations (pictured in the "friezes" of Fig. 1) L seems smaller on certain days and on other days unmistakably magnified; on at least one out of every ten days the magnification-factor for L can be estimated as two or higher.

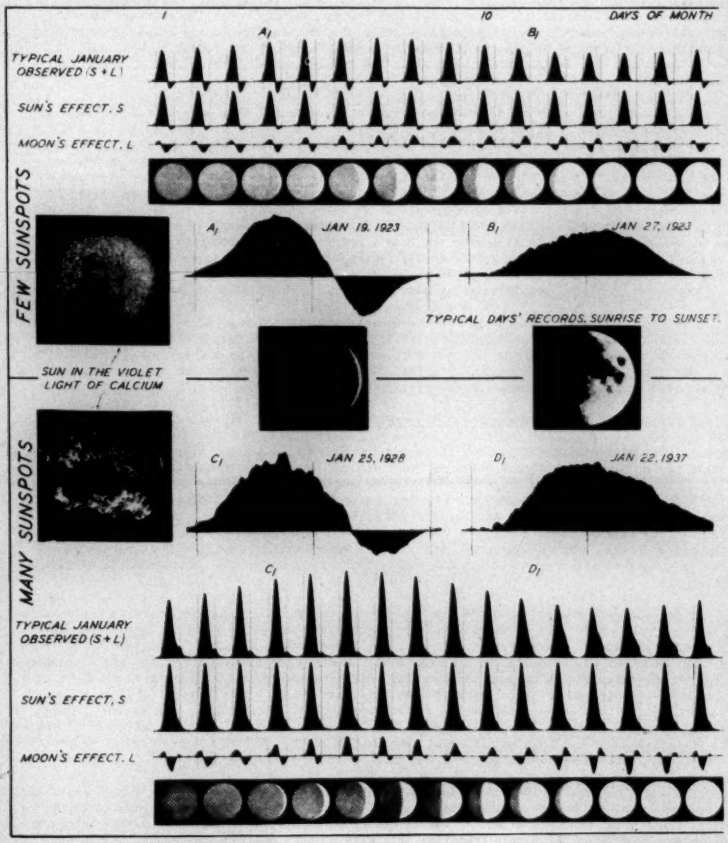
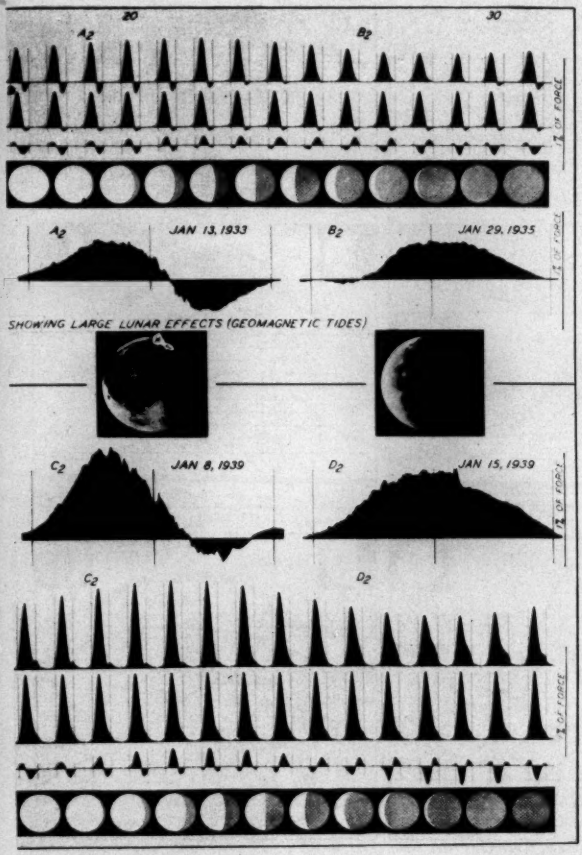


FIG. 1—DAILY CHANGES OF GEOMAGNETIC HORIZONTAL FORCE CAUSED BY
MUM, HUANCAYO MAGNETIC OBSERVATORY, PERU (PHOTOGRAPHS OF

To investigate this variability of both S and L is, of course, more difficult and the evidence is less compelling than in the case of the average variations. But the inspection of a large number of daily magnetograms leaves no doubt that the abnormal shapes of certain daily curves are caused by an accentuation of L and not simply by a change of S. Such cases are most conspicuous at those phases of the Moon when the L-curve has large deviations (from the night level) between 14^h to 18^h, because the main swing of S occurs in the forenoon so that in the afternoon the comparatively steady trend of S allows L to dominate the observed curve (S+L).

Therefore, in the search for "Big L-days" in January, days with the Moon's ages of about $\nu = 2$(or 14) and $\nu = 8$(or 20) hours appear most suitable. The days with $\nu = 2$, 8, 14, and 20 hours are marked by the letters A_1, B_1, A_2, B_2 on the frieze for sunspot-minimum, and by C_1, D_1, C_2,



SUN AND MOON DURING SUNSPOT MINIMUM AND MAXI-
SUN AND MOON FROM MOUNT WILSON OBSERVATORY)

D_2 on the frieze for sunspot-maximum. On the days marked A or C, L has a downward swing in the afternoon and on the days marked B or D, L has an upward swing in the afternoon; these features appear in the observed curves for (S+L) as a conspicuous downward swing in the afternoon on the days marked A or C in contrast to the days marked B and D in which the forenoon maximum (S+L) is protracted well into the afternoon. Actual daytime records of H between 06^h and 18^h for 'Big L-days' are reproduced in the center of Figure 1 and are marked by the same letters A,

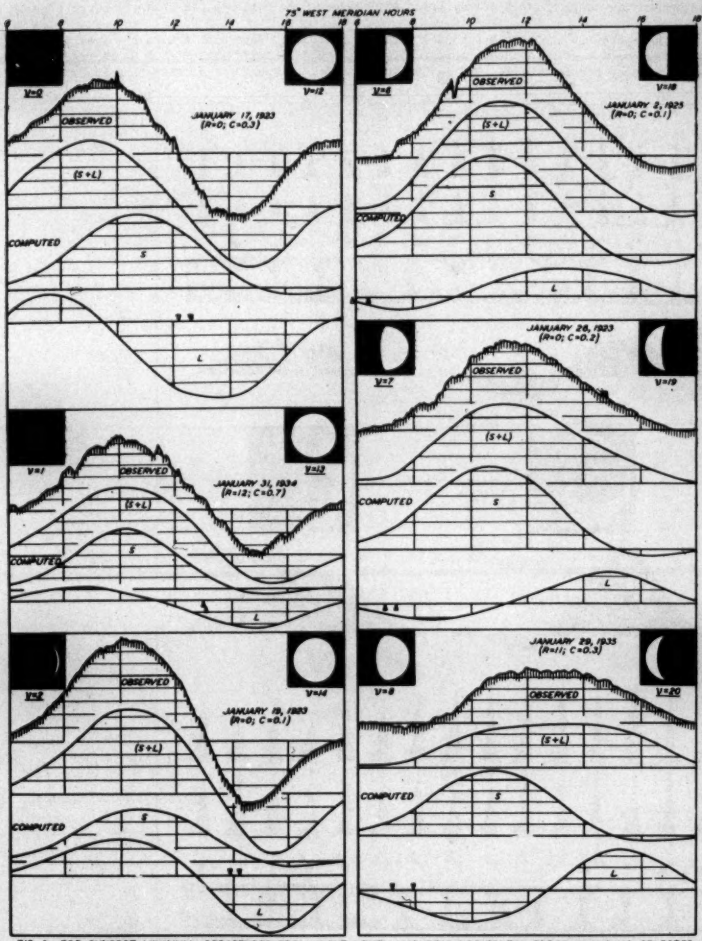


FIG. 2—FOR SUNSPOT-MINIMUM; DEPARTURES FROM NIGHT-LEVEL, MAGNETIC HORIZONTAL FORCE, HUANCAYO, SELECTED QUIET DAYS WITH CONSPICUOUS GEOMAGNETIC TIDES IN JANUARY SHOWING INVERSION LEFT TO RIGHT OF TIDAL EFFECT WITH AGE (N) OF MEAN MOON IN HOURS—UNDERSCORED FOR DATE GIVEN WHICH ALSO TYPIFIES (N±12); R=SUNSPOT-NUMBER; C=MAGNETIC CHARACTER-FIGURE; UPPER AND LOWER TRANSITS: ↓ FOR MEAN MOON, ↓ FOR APPARENT MOON; SCALE 20γ PER DIVISION

B, C, D, with the Moon's phase indicated by actual photographs taken at Mount Wilson Observatory and kindly provided by Dr. F. E. Wright. These selected records show the lunar influence more pronounced than the friezes and demonstrate its tidal origin as well in the similarity of the curves A_1 and A_2, B_1 and B_2, C_1 and C_2, D_1 and D_2--for which the age ν of the Moon differs by 12 hours, interchanging the times of upper and lower transits--as in the different shapes of the curves on days for which ν differs by six hours.

For the selection of these days the magnetograms from 1923 to 1939 were available; magnetic disturbance limits the choice so that not more than about eight days were available from which to choose each of the eight records reproduced. Nevertheless, two of the contrasting pairs of magnetograms shown are for January days only a quarter-month apart, namely, A_1 and B_1, and C_2 and D_2.

(4) Attempt to separate solar and lunar daily variations on individual days--After the success of this preliminary survey all January magnetograms were systematically searched for "Big L-days". Two model sets referring to sunspot-minimum and maximum were selected. Each set consists of 12 daytime curves, namely, one curve for each age ν of the Moon to the nearest hour with no distinction made between the ages ν or $(\nu \pm 12)$. Only quiet days were considered for this purpose--the highest international magnetic character-figure C for one day was 0.9--so that about 16 magnetograms were available from which to select each curve. Since in most cases several magnetograms were found just as typical as the one finally selected for each age ν, it can be said that out of every ten days in January at least one shows L as prominently as the days of the two model sets.

A daily variation of H can be considered as given by a row of the 12 hourly means between 06^h and 18^h, expressed as departures ΔH from the night level and corrected for non-cyclic variation. For a given sunspot-number the average S (S°, say) and the average L (L°, say) for each age ν of the Moon in January can be expressed in that way and likewise the individual daily record for a selected "Big L-day"; by least-square methods, two magnification factors a and b can then be found, so that $aS^\circ + bL^\circ$ fits the observed curve best.

Figure 2 is a sample for sunspot-minimum of four drawings expressing the model sets of "Big L-days". The curves marked "Computed (S + L), S, and L° are ($aS^\circ + bL^\circ$), aS°, and bL°. The "Computed (S + L)"-curves approximate the "observed" magnetograms satisfactorily. The contrast is striking between the curves shown at the left and at the right for values of the age ν six hours apart, equivalent to a quarter-month, and the analysis shows the cause of this contrast in the reversal of L. The departures of bL° from the night-level reach sometimes 100Y. Of course, the "computed" curves should not be interpreted too rigidly because the analysis does not take into account the possibility that the maxima and minima of S or L may shift from those of S° and L°, or that the magnification-factors a and b may change in the course of the day.

As already mentioned, the separation ($aS^\circ + bL^\circ$) is feasible where the two rows of the 12 hourly departures expressing S° and L° are not much correlated. But if S° and L° are so similar that the correlation-coefficients between the two rows approach +1 or -1, the separation becomes uncertain. This is the case for ages ν near 4 (or 16) and 10 (or 22) hours. It is found, however, that individual days with abnormally small ranges of the observed curves occur preferably near ν = 10 or 22, when L° is the reversed S°-curve, so that a big L is then recognized in the compensation of S.

(5) Possibility of large lunar effects at other observatories--After the existence of such large lunar daily variations has once been recognized for Huancayo, it seems likely that similar conditions might be found for other observatories. The magnitude of L has been so far judged by the amplitude c_2 of its semidiurnal sine-wave $c_2 \sin (2\tau + \alpha_2)$--with lunar mean time τ, as usual, reckoned from 0° to 360° between successive lower transits--which does not exceed a few Y; even for Huancayo H, in January, at sunspot-minimum, c_2 is only 7.4Y. But it must be realized that c_2 gives the average effect for 24 hours to which the night hours contribute practically nothing, while near noon the lunar effect may be several times larger. Preliminary calculations for declination at Watheroo confirm this expectation.

In the light of these new facts former studies on the "variability of S from day to day" need revision with respect to the unexpected effect of L. Also the rigid manner in which a number of observatories regarded certain "quiet-day variations" as standards from which every deviation was regarded as "disturbance" appears now even less justifiable. The new experience favors the flexibility with which, in scaling the new three-hour-range index K for magnetic activity, the non-K-variation (S + L) is to be estimated.

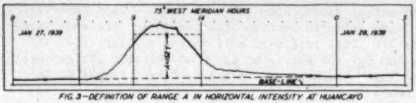


FIG. 3—DEFINITION OF RANGE A IN HORIZONTAL INTENSITY AT HUANCAYO

(6) General purpose of measuring daily ranges A--The present paper was begun as part of a program (to be described elsewhere) to utilize the changes in the magnetic quiet-day solar variation S for a study of changes in the solar ionizing wave-radiation W. Usually S is visualized as due to the well-known ionospheric current-systems consisting mainly of two current-vortices with foci centered on the 11^h-meridian near the latitudes 35°; more roughly S can be pictured as the field of a gigantic vertical horseshoe-magnet in the meridian preceding noon by an hour, with the south pole moving along 35° north latitude and the north pole moving along 35° south latitude. Both the current-system and the more schematic analogy of the horseshoe-magnet simulate those typical features of S by which the intensity of the S-system can be measured, namely, expressed for the magnetic force components X (north), Y (east), and Z (down): At equatorial stations, the rise in daytime of X over the night level; at stations in northern middle latitudes, the swing of Y between a morning maximum and an afternoon minimum and the daytime depression of Z when the south pole passes overhead; at stations in southern middle latitudes, the reversed variations in Y and Z.

Figure 3 shows, for Huancayo, how the intensity of S in H (practically identical with X) is measured by the range A, defined as the excess of the average of H for the five-hour interval 09^h to 14^h (75° west meridian standard time) over the night level, which is provided by a straight line connecting successive five-hour averages 00^h to 05^h. The lunar daily variation L appears in A as a semimonthly wave (as easily recognized in the friezes of Fig. 1), which must be eliminated before the corrected ranges A can be used to measure S. The unexpected magnitude of these semimonthly waves led to the present study. The following sections will deal with this average lunar effect.

(7) Lunar semimonthly waves in A; change with sunspot-cycle--How well these lunar variations

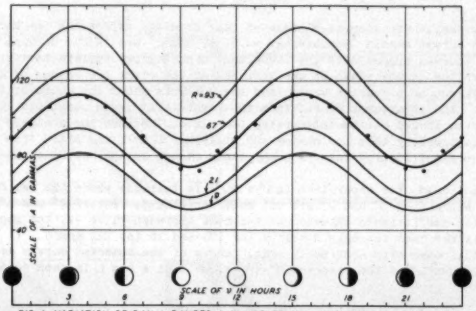


FIG. 4—VARIATION OF DAILY RANGES A IN HORIZONTAL INTENSITY AT HUANCAYO, DECEMBER SOLSTICE, 1922–39, WITH AGE V OF MOON AND RELATIVE SUNSPOT-NUMBER R [OBSERVED TOTAL AVERAGES (DOTS) AND SEMIMONTHLY SINE-WAVES]

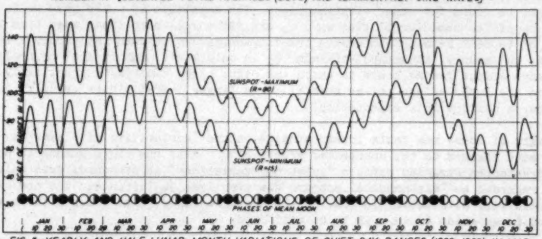


FIG. 5—YEARLY AND HALF LUNAR-MONTH VARIATIONS OF QUIET-DAY RANGES (1922–1939) IN MAGNETIC HORIZONTAL FORCE, HUANCAYO, REFERRED TO NEW MOON ON JANUARY 1

in the ranges A fit semimonthly sine-waves is shown in Figure 4; the dots near the curve at the center give the actual averages of A obtained by grouping all ranges A in the months November to February, 1922-39, according to the age of the Moon [for ν and ($\nu \pm 12$) averaged promiscuously], with the semimonthly sine-wave obtained by harmonic analysis. Figure 4 gives also the lunar semimonthly sine-waves in A for four groups according to the relative sunspot-number R; numerical data are given in Table 1.

Table 1--Average daily ranges A in four groups according to sunspot-number R and lunar semimonthly sine-waves expressed by the highest and lowest ranges A and the lunar age ν_{max} of the day with the highest range. Horizontal magnetic force, Huancayo Magnetic Observatory, November to February, 1922-1939

Sunspot-number R	9	21	67	93	Total mean
Average A	66	76	107	124	93γ
ν_{max}	3.4	3.6	3.6	3.6	3.6 hours
Highest A	81	94	126	149	112γ
Lowest A	51	58	88	99	74γ
Ratio	1.59	1.62	1.44	1.51	1.52

A is roughly doubled from sunspot-minimum to sunspot-maximum; it is surprising to note that the lunar effect in A reaches within one-half month nearly the magnitude of the effect of the 11-year sunspot-cycle.

(8) Change with the season--The lunar semimonthly wave in A is largest in January and February and smallest in June. This does not conform with the annual variation in A itself (that is, in S) as expressed in the monthly means of the ranges which is a double wave with maxima near the equinoxes and minima near the solstices. Figure 5 shows, for sunspot-maximum and sunspot-minimum, the ranges A throughout a year (supposed to begin with new Moon), under the superposed effect of the annual variation of S and of the lunar semimonthly wave; this diagram (and Table 2) shows also the phase shift; the maximum of the lunar semimonthly wave occurs in June earlier than in December. The results confirm previous experience that the seasonal variations in L are larger than those in S; Huancayo, at the northern edge of the southern ionospheric current-circuit of L, shows the seasonal waxing and waning of the current-density of this circuit.

Table 2--Daily ranges A in horizontal magnetic force, Huancayo, 1922-1939: Monthly averages and lunar semimonthly sine-waves of amplitude c (= half difference highest minus lowest range) and maximum at age ν_{max} of mean Moon

Parameter	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Average A, γ	100.6	104.5	114.2	108.6	89.1	75.2	79.4	89.8	112.8	116.6	88.1	86.4
c, γ	23.1	24.0	15.7	14.3	6.7	5.3	6.1	7.6	9.4	11.1	14.0	20.2
ν_{max}, hours	4.4	3.1	2.3	2.5	1.7	0.3	1.7	1.9	1.4	2.4	2.9	3.4

Figure 6 represents, in harmonic dials for the lunar semimonthly waves in the daily ranges A, their average change with season [upper part, smoothed from month to month by formula $(a + 2b + c)/4$], and, for the usual groups of four calendar months, the change with the sunspot-cycle; here the months May to August (= June solstice), in which L is small, react differently than the other two groups.

(9) Change with magnetic activity--While all the other parts of this study deal with undisturbed days, with international magnetic character-figure C under 1.2, it was thought desirable to test the effect of magnetic activity on L in at least one significant case. The months December, January, and February at sunspot-maximum were selected as most suitable since L is large in that season and since the disturbance is greater than at sunspot-minimum. The average ranges A and the lunar semimonthly waves were computed for the 136 disturbed days ($C \geqq 1.2$) and they are compared below with the results for the undisturbed days in the same months:

Undisturbed days $\quad A = 119.5\gamma + 24.2\gamma \sin (2\nu + 340°)$
Disturbed days $\quad A = 112.0\gamma + 21.6\gamma \sin (2\nu + 299°)$

The slight reduction of the average range A from 119.5γ to 112.0γ is an effect of the solar

disturbance-daily variation S_D. The effect of magnetic activity on the lunar semimonthly wave is not large; in fact, considering the uncertainty introduced by the great irregular fluctuations of A on these disturbed days (values between -68γ and +235γ), the similarity of the wave for disturbed and undisturbed days is rather surprising.

(10) Lunar semimonthly waves for each hour of the solar day--The lunar semimonthly sine-waves in the daily ranges A are a combination of such waves appearing in the hourly means for each fixed hourly interval, which will be considered next. For instance, in the average for the months December, January, February, 1922-1939, the hourly means of H for the interval 11^h to 12^h standard time are found to contain the lunar semimonthly wave 30.5γ sin (2ν + 341°). These lunar semimonthly waves for each hourly interval according to mean solar time, t, have been expressed in the harmonic dial (Fig. 7A) as

$$c(t) \sin [2\nu + \alpha(t)]$$

The function c(t) is the solar daily variation of the amplitude of the lunar semimonthly wave at the solar hour t; it is expressed in Figure 7A by the radius from the origin and in Figure 8 by the dots (for the observed values) and a smooth curve. c(t) can be assumed to express the current-density of the ionospheric current; assuming S. Chapman's estimate that 0.6 ΔH is the contribution of the primary exterior ionospheric currents to the horizontal field change

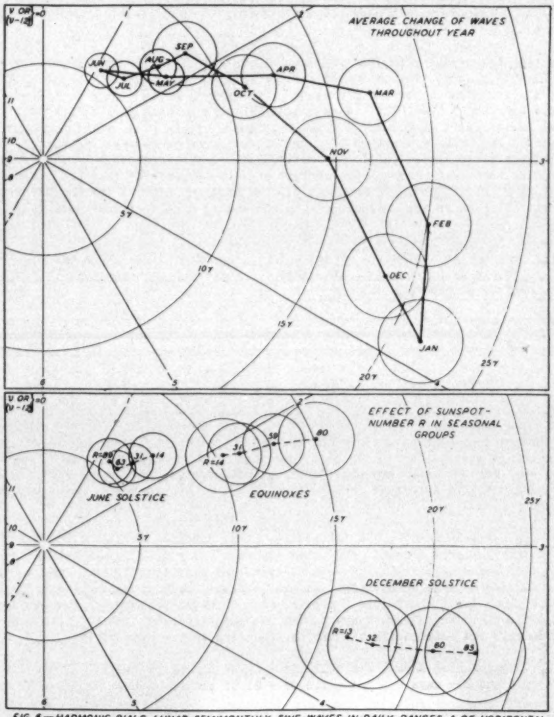


FIG. 6—HARMONIC DIALS, LUNAR SEMIMONTHLY SINE-WAVES IN DAILY RANGES A OF HORIZONTAL INTENSITY AT HUANCAYO, 1922-39 [AVERAGES WITH PROBABLE-ERROR CIRCLES]

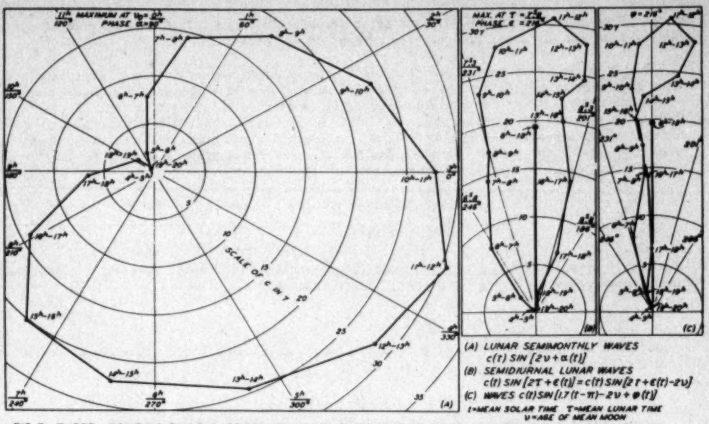

(A) LUNAR SEMIMONTHLY WAVES
c(t) SIN [2υ + α(t)]
(B) SEMIDIURNAL LUNAR WAVES
c(t) SIN [2T + ε(t)] = c(t) SIN [2 τ + ε(t) - 2υ]
(C) WAVES c(t) SIN [1.7 (t - π) - 2υ + φ(t)]
t = MEAN SOLAR TIME T = MEAN LUNAR TIME
υ = ABE OF MEAN MOON

FIG. 7—THREE HARMONIC DIALS EXPRESSING LUNAR GEOMAGNETIC TIDES IN HORIZONTAL INTENSITY AT HUANCAYO, DECEMBER, JANUARY, AND FEBRUARY, 1922–39

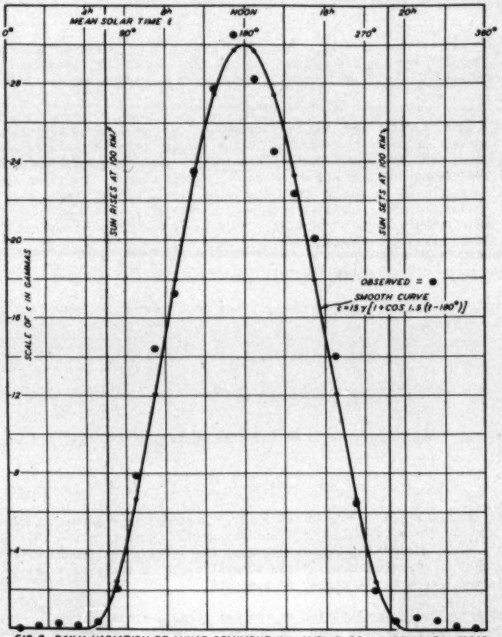


FIG. 8—DAILY VARIATION OF LUNAR SEMIMONTHLY AMPLITUDE c, HORIZONTAL FORCE, HUANCAYO, DECEMBER, JANUARY, AND FEBRUARY 1922–39

ΔH, an increase of H by 1γ is produced by an ionospheric current from west to east of surface-density 1 amp/km, or about 1100 amperes across 10° of latitude.

Two features dominate the function c(t): The contrast between day and night, and the symmetry in the morning rise and the evening decrease. There is an asymmetry around noon; from 11^h to 14^h the observed function c(t) looks as if it is shifted about half an hour earlier than according to symmetry with respect to noon. But, on the whole, the observed function is quite satisfactorily approximated by a zero-line in the eight night hours centered at midnight, and a sine-curve of 16-hour period, with its maximum at noon. Reckoning solar time as usual from 0° to 360° starting at midnight, the curve from 04^h to 20^h is

$$c(t) = 15\gamma\,[1 + \cos 1.5(t - 180°)]$$

drawn in Figure 8.

(11) A complete formula for the lunar effect--Between mean solar time t and mean lunar time τ, both reckoned in degrees from the lower transits, the relation is

$$\tau = t - \nu$$

We can therefore express the lunar semimonthly waves as lunar semidiurnal waves of variable amplitude c(t); replacing ν by $(t - \tau)$ we obtain

$$c(t)\,\sin[2\nu + \alpha(t)] = c(t)\,\sin[2t - 2\tau + \alpha(t)] = c(t)\,\sin\,[2\tau + \epsilon(t)]$$

with

$$\epsilon(\tau) = 180° - \alpha(t) - 2t$$

These waves are represented in Figure 7B; this harmonic dial is turned so that the vector representing the average lunar semidiurnal wave for the daytime 06^h to 18^h points upward; the phase of this average wave is actually $\epsilon = 216°$ according to a maximum for $\tau = 117°$ or 7.8 hours mean lunar time.

Figure 7B shows clearly that maxima (and minima) of the lunar semidiurnal waves occur, with respect to the Moon, about an hour earlier in the morning than in the afternoon. In other words, on each individual day, the time between a morning maximum and the following afternoon minimum of the lunar semidiurnal wave is not 6 but about 7 lunar hours. The lunar-wave variation in daytime has therefore the appearance of a sine-wave with a period longer than half a lunar day; but from day to day its phase-angle at noon shifts regularly with mean lunar time, as if the wave over night catches up with lunar time. Instead of the lunar semidiurnal wave of variable amplitude c(t) and phase-angle $\epsilon(t)$ written in mean solar time t

$$c(t)\,\sin\,[2\tau + \epsilon(t)] = c(t)\,\sin\,[2t + \epsilon(t) - 2\nu]$$

the lunar variation is therefore better expressed by a wave of frequency 1.7 per solar day, or period 24/1.7 = 14 hours

$$c(t)\,\sin\,[1.7(t - 180°) - 2\nu + \varphi(t)]$$

better in the sense that the phase-angle $\varphi(t)$ is more nearly constant throughout the day than $\epsilon(t)$.

Figure 7C expresses this fact. Inserting the expression for c(t) and the average value $\varphi = 216°$, we obtain

$$15\gamma\,[1 + \cos 1.5\,(t - 180°)]\,\sin\,[1.7\,(t - 180°) - 2\nu + 216°]$$

as the general formula which expresses the observed average geomagnetic tidal effect of the mean Moon on H at Huancayo from 04^h to 20^h in the average for the months December, January, and February, 1922-39, by four parameters, namely, an amplitude (15γ), two frequencies (1.5 and 1.7), and a phase-angle (216°). The influence of the sunspot-cycle is practically restricted to an increase of the amplitude with the number of sunspots.

(12) Discussion and interpretation of the new formula--This expression needs less parameters and seems therefore more adequate than the ordinary harmonic analysis which expresses the lunar

variation by eight parameters, namely, the amplitudes and phase-angles of four superposed sine-waves (with constant amplitudes) of frequencies 1, 2, 3, and 4 per solar day and phase-angles decreasing like (-2ν), according to Chapman's phase-law. Of course, the new expression can be developed in a series of such ordinary sine-waves with constant amplitudes; this has been done, as will be described elsewhere, and the phase-law terms have been found to be indeed the most important ones.

From the standpoint of the dynamo-theory the new expression is easily interpreted, thus, in turn, strengthening confidence in that theory. Consider the current-circuits in the Southern Hemisphere which in December to February cause the lunar waves L in H at Huancayo. If hourly values were rearranged in rows corresponding to lunar days the average row for the lunar month would be a regular lunar semidiurnal wave of constant amplitude corresponding to four ionospheric current-circuits equally intense and equally spaced around the Southern Hemisphere, each covering an octant of a fictitious homogeneous ionosphere in which the solar daily variations of ion-content have been averaged. On each particular day only the current-circuits on the daylight side are active and the highest conductivity is confined to the eight hours from 08^h to 16^h. The current-circuits in that part of the ionosphere will therefore "expand" from the noon meridian toward the meridians of sunrise and sunset, feeding, so to say, on those circuits which are partly or wholly suppressed on the night side.

(13) The suppression of the lunar wave at nighttime--Figure 8 indicates that the current-intensities in the ionosphere are highest near noon and do not show any conspicuous lag behind the daily change in the Sun's altitude. This feature agrees with directly observed changes in ion-density in the low ionosphere (E-region). The seat of the main lunar currents must therefore also be low in the ionosphere, in regions in which the recombination is fast, so that ion-production and ion-attachment are in approximate equilibrium, certainly not as high as the F-region which shows an appreciable lag.

The observed values of the amplitudes c(t) for the night hours plotted in Figure 8, small as they are, still are exaggerated; they represent not so much the actual waves as "error-waves" due to uncertainties not sufficiently eliminated in the available series of observations. A more reliable estimate is possible by using the changes from hour to hour (more exactly from one hourly mean to the next hourly mean) and by determining an average lunar semidiurnal wave in these changes by the same process as the average lunar wave for 06^h to 18^h was obtained in Figure 7B. This gives for the six night hours, 21^h to 03^h, $0.07\gamma \sin (2\nu + 327°)$, and for the six daylight hours, 09^h to 15^h, $11.40 \sin (2\nu + 243°)$. The phase-angles refer to midnight and noon, respectively; they should be nearly equal in a pure semidiurnal wave and the fact that they differ by as much as 84° can only be attributed to the uncertainty in the night hours. This makes the ratio of the lunar current-intensities at day and at night

$$(\text{Noon/midnight}) = (11.40/0.07) = (160/1)$$

only an approximation, but it is more likely that the actual night values would be even smaller. In fact, more detailed calculations based on changes in bihourly means from the six-hour intervals 22^h to 04^h and 09^h to 15^h yield the ratio

$$(19.97\gamma/0.04\gamma) = (500/1)$$

It had been considered possible that the induced currents in the Earth's interior, where day and night are irrelevant, might spread from the daylight to the night hemisphere so as to veil by their magnetic effects the primary effects of the ionospheric currents. The present result shows convincingly that neither ionospheric nor induced lunar currents cross the night hemisphere in equatorial regions.

(14) Lunar semimonthly wave in the daily means--After it had been realized that there is practically no lunar variation in the night hours, the semimonthly waves in the daylight hours could be ascertained more accurately by using not the absolute hourly means but their departures from the night level. This procedure eliminates automatically the influence of the ring-current effect which otherwise would veil the lunar effect by large fictitious semimonthly waves.

Another theoretical consequence of the suppression of L in the night hours is a lunar semimonthly wave to be expected in the ordinary daily means for 24-hour intervals from midnight to midnight. This feature is quite distinct in the frieze for L in Figure 1. Superposition of all lunar semimonthly waves in the hourly means, months December to February, 1922-39, yields

$$3.97\gamma \sin (2\nu + 330°)$$

for the wave to be expected in the daily means of H.

This wave is veiled by the ring-current effect which produces the much greater change in the daily means of H expressed in the u-measure of magnetic activity; in January 1938, for instance, the average change of H from day to day was 28γ. But since it seemed of interest to confirm directly the prediction of a lunar semimonthly wave in the daily means of H the following calculation was made: For each day with international character-figure C under 1.2, in the months December, January, February, 1922-39, the departure of the ordinary daily mean of H from the monthly mean was formed. For each calendar month these departures were separated in two groups comprising each one-fourth (= 90°) of the semimonthly period, namely, days around the expected maximum of the semimonthly wave (with the ages ν = 3, 4, 5; 15, 16, 17 hours) and days around its minimum (with ν = 9, 10, 11; 21, 22, 23 hours). The average departure for the "minimum" group was subtracted from the average departure for the "maximum" group to form a difference for each month. Of the 51 differences (for 51 months) thus formed, 40 are positive, 10 negative, and one zero; the average difference for all months is +6.2γ with a standard deviation of 1.1γ. This difference exceeds its standard deviation more than fivefold; it agrees well with the predicted value, namely—applying the factor sin $(\pi/4)/(\pi/4)$ = 0.90 for the smoothing of a sine-wave over an interval of 90°—+ 2 × 3.97γ × 0.90 = +7.1γ.

This result is incidentally another argument for reducing field-observations not to the ordinary "daily mean", but to a night level corrected for ring-current effects.

(15) Effect of lunar distance on the tide-producing forces--The dynamo-theory connects the lunar geomagnetic tides with the tides in the atmosphere and these are governed by the tide-producing forces of lunar semidiurnal period. At perigee, when the Moon is nearest to the Earth, these forces are 18.8 per cent greater than on the average, and at apogee, when the Moon is farthest away, they are 13.8 per cent smaller than on the average. If the atmospheric tides were proportional to the tide-producing forces, and in phase with them, the lunar geomagnetic tide at perigee would have greater amplitudes than at apogee, in the ratio [(100 + 18.8)/(100 13.8)], or approximately (11/8); the phase-angles would be the same.

But this periodic change in amplitude would not be the only variation of the tides in the course of an "anomalistic month" reckoned from one perigee to the next. To describe the full effect we divide (following Chapman) the anomalistic month (of 27.555 days) into four quarters, centered at PER = perigee and APO = apogee and two points between, namely, REC = "Receding" between perigee and apogee, and NEA = "Nearing". When the Moon is nearer to the Earth it moves faster in its orbit; and since this orbital motion causes the Moon to appear later from day to day, this apparent lag against the Sun is accentuated near PER and diminished near APO. Or, compared with the evenly moving mean Moon, the apparent Moon loses in the half month from NEA over PER to REC, and gains in the other half month. The effects accumulate so that the tide expressed in mean lunar time τ will appear most retarded at REC and most accelerated at NEA.

(16) The partial tides expressing the effect of lunar distance--The classical harmonic analysis of the tidal forces expresses the influence of the lunar distance by a superposition of sine-terms of constant amplitudes and different frequencies. It considers three time-variables, all progressing at even rate, namely, mean lunar time τ, mean longitude of the Moon, and mean longitude p of the perigee, so that (s - p) is the Moon's distance from its perigee. Putting the amplitude of the main lunar semidiurnal term M_2 equal to 100 units, the semidiurnal time-variations of the lunar tidal forces at any locality are expressed mainly by four "partial tides" designated by standard symbols, namely

$$M_2 = 100.00 \cos 2\tau$$

$$N_2 = 19.15 \cos [2\tau - (s - p)]$$

$$L_2 = -2.83 \cos [2\tau + (s - p)]$$

$$2N = 2.53 \cos [2\tau - 2(s - p)]$$

The superposition of these terms is best visualized in the harmonic dial, Figure 9, for the frequency 2τ, which pictures the lunar semidiurnal waves at 36 intervals throughout the anomalistic month in the successive stages of superposition up to $(M_2 + N_2 + L_2 + 2N)$. At REC the semidiurnal wave comes nearly half an hour later and at NEA nearly half an hour earlier as compared with the main term M_2 which is equivalent with the effect of the mean Moon at constant mean distance.

(17) Method for computing distance-effects--The accurate computation of these influences of the lunar distance on L requires a combination of many observations in order to eliminate the variability of L and other detrimental influences. While the main term (M_2) in L performs a series of cycles with respect to the Sun within half a (synodic) month, the main distance term (N_2) requires a full (anomalistic) month for completing a series of cycles; therefore, N_2 is, so to say, more vulnerable to spurious effects of the S-variability with its quasi-persistent 27-day recurrence-tendency.

The anomalistic month was divided into four quarters, namely, seven days each centered at the mean perigee and the mean apogee [taken from the "Mondtafeln", 3] and the remaining two quarters REC and NEA (adopting the subdivision introduced by S. Chapman). The semimonthly waves in the ranges A were determined separately in these four quarters for each month individually and the results were expressed as lunar semidiurnal waves (as in section 11). A subsequent transformation of the harmonic dial for lunar semidiurnal waves represented the main geomagnetic tide M_2 as vector of 100 units' length, pointing upward, and the four individual results for the quarters as additional vectors starting from the endpoint of the M_2-vector. In this way the large seasonal variation of M_2 is eliminated and the results for the months can be superposed, pro-

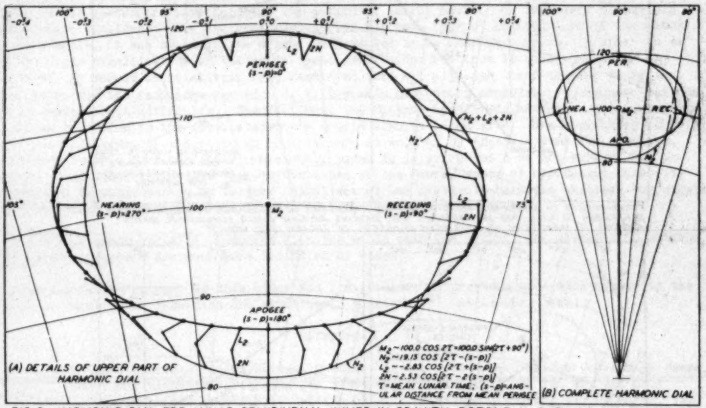


FIG. 9—HARMONIC DIAL FOR LUNAR SEMIDIURNAL WAVES IN GRAVITY-POTENTIAL SHOWING INFLUENCE OF LUNAR DISTANCE; PARTIAL TIDES N_2, L_2, 2N SUPERPOSED ON MAIN TIDE M_2

vided the assumption is valid that the lunar distance effect relative to the main L-term M_2 is not much affected by season, which seems reasonable on the basis of our knowledge about atmospheric tides. In combining the monthly results greater weight has been given to the months with large L-variations because they will show the distance-effects more accurately.

(18) Results on the effects of lunar distance on geomagnetic tides--The results for the months September to April, 1922-39, are shown in Figure 10. The observed tides in the four quarters are shown with their probable-error circles and they are to be compared with the quarterly "theoretical" averages computed from Figure 9. Obviously the observed influence of lunar distance is quite marked, but it differs in character from the simple "theoretical" relationship in the tidal forces. The main change of the lunar semidiurnal wave from PER to APO is not (as in the "theoretical" case) a decrease in amplitude, but a shift in the phase-angle of the lunar semidiurnal wave, the maximum at APO occurring 0.9 hour later than at PER. This agrees qualitatively with Chapman's results for other observatories and supplements them with reference to the well-known partial tides of the tidal forces; his early calculations did not permit this reference since they were based on apparent lunar time, the lunar transits being taken from the Astronomical Year Book. While the "theoretical" change of the lunar semidiurnal wave from REC to NEA is merely an acceleration, the "observed" change is a decrease in amplitude from 127 to 76 units. In all the "observed cross" expressing L in the four quarters is obtained from the "theoretical cross" expressing the tidal forces by enlarging the theoretical cross and turning it toward the left by nearly a quarter-month.

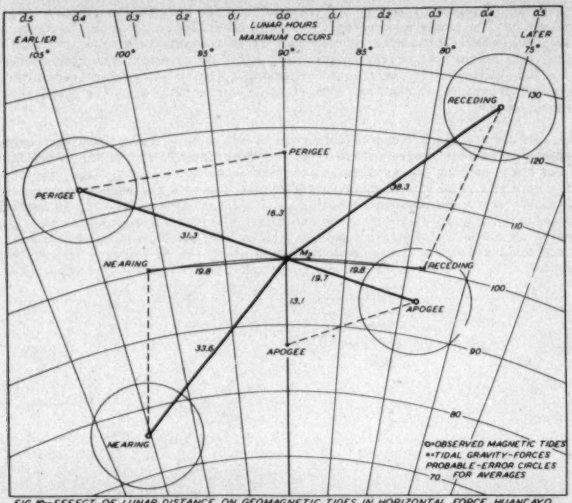


FIG. 10—EFFECT OF LUNAR DISTANCE ON GEOMAGNETIC TIDES IN HORIZONTAL FORCE, HUANCAYO, SEPTEMBER TO APRIL, 1922-39; HARMONIC DIAL SHOWING AVERAGE LUNAR SEMIDIURNAL WAVES ADDITIVE TO MAIN TERM M_2, FOR FOUR QUARTERS OF ANOMALISTIC MONTH

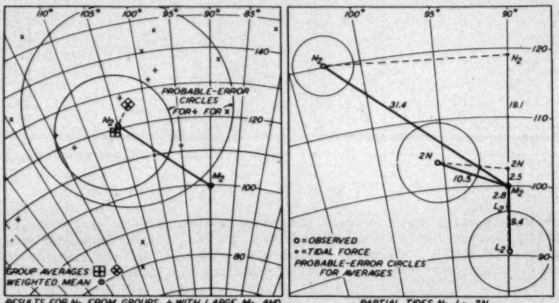


FIG. 11—EFFECT OF LUNAR DISTANCE ON GEOMAGNETIC TIDES IN HORIZONTAL FORCE, HUANCAYO, SEPTEMBER TO APRIL, 1922-39—PARTIAL TIDES RELATIVE TO M_2, EXPRESSED IN HARMONIC DIALS FOR LUNAR SEMIDIURNAL WAVES

The four results for the quarter months allow a separation into the four partial tides M_2, N_2, L_2, 2N. Figure 11 shows, at the left, how individual results for N_2 were combined with weights according to the absolute amplitude of the main term and, at the right, final total averages for the partial geomagnetic tides relative to M_2. Only N_2 is determined with certainty, its probable-error circle being less than one-seventh of its amplitude. If the main term is put equal to

$$M_2 = 100.0 \sin (2T + 90°)$$

in the ("theoretical") tidal forces, and

$$M_2 = 100.0 \sin (2T + 90° + \Delta\epsilon)$$

in the observed geomagnetic tides (with $\Delta\epsilon$ varying with the season, being (216° - 90°) = 126° in the average for December, January, and February), the "theoretical" partial tide in the tidal forces is

$$N_2 = 19.1 \sin [2\tau + 90° - (s - p)]$$

to be compared with the observed geomagnetic partial tide

$$N_2 = 31.4 \sin [2\tau + 90° - (s - p) + \Delta\epsilon + 56°]$$

with a probable-error circle of 5.2 units.

(19) The significance of these results--The results expressed in Figures 10 and 11 are important for the theory of the geomagnetic and the atmospheric tides. New discussions on atmospheric tides have to reconcile these implicit geomagnetic data about semidiurnal ionospheric motions with the observed barometric tides and the theory of atmospheric oscillations.

Of special interest is the fact that N_2, with its period of 12.658 hours, is apparently stronger in the ionosphere than M_2, with its period of 12.421 hours. On the basis of the old theories which considered only one resonance-period for each type of oscillations of the atmosphere as a whole, it was necessary to assume this period to be near 12.0 hours, in order to explain the large magnification of the solar semidiurnal tide; but then it would be hardly explicable why N_2 should be relatively more magnified than M_2, although the frequency of N_2 is farther away from the resonance-period. G. I. Taylor's new theory of multiple resonance-periods, however, removes this difficulty. The fact that the M_2-wave apparently swings in the ionosphere in opposite direction to the lower atmosphere should also be considered. New approaches to this problem seem necessary by reduction of observations as well as by theory. Even for Huancayo, the results obtained from the lunar semimonthly waves in daily ranges A do not exhaust the information about lunar influences that is contained in the hourly means of horizontal intensity and they will be supplemented by further reductions of the available harmonic analyses for single days. The search for diurnal tides, futile so far, should also be resumed.

One result seems certain: Compared with the winds near the ground, the atmospheric motions in the lower ionosphere are much more dominated by tides.

A more detailed account of this study and its relation to previous work will appear in the "Journal of Terrestrial Magnetism and Atmospheric Electricity" [September, 1940].

References

[1] S. Chapman and J. Bartels, Geomagnetism, 2 vols., xxviii + 1049 pp., Oxford University Press, 1940. (The lunar magnetic variations are discussed in chapters 5, 9, 19, 20, and 23.)
[2] Terrestrial magnetism and electricity, edited by J. A. Fleming. (Physics of the Earth, vol. VIII), xii + 794 pp., McGraw-Hill Book Company, New York and London, 1939.
[3] J. Bartels and G. Fanselau, Geophysikalische Mondtafeln 1850-1975. Geophys. Inst. Potsdam Abh. No. 2, 44 pp., J. Springer, Berlin, 1938. (These tables supplement the same authors' "Geophysical lunar almanac," Zs. Geophysik, v. 13, pp. 311-328, 1937; partly translated in Terr. Mag., v. 43, pp. 155-158, 1938.)

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PHYSICAL REPRESENTATIONS OF THE GEOMAGNETIC FIELD

A. G. McNish

The familiar Gaussian analysis of the geomagnetic field by the method of spherical harmonics clearly indicates that the predominant portion of the so-called permanent magnetism of the Earth is due to internal causes. One of the striking results of this analysis is the dominance of the harmonics of the first degree. These first-degree harmonics may be physically represented by a dipole at the center of the Earth with its south-seeking end directed toward a point in latitude 78°5 north, longitude 291°2 east. An improved representation of the field which partially takes into account harmonics above the first degree is furnished by shifting this dipole 342 km toward a point in latitude 6°5 north, longitude 161°8 east [see 1 under "References" at end of paper].

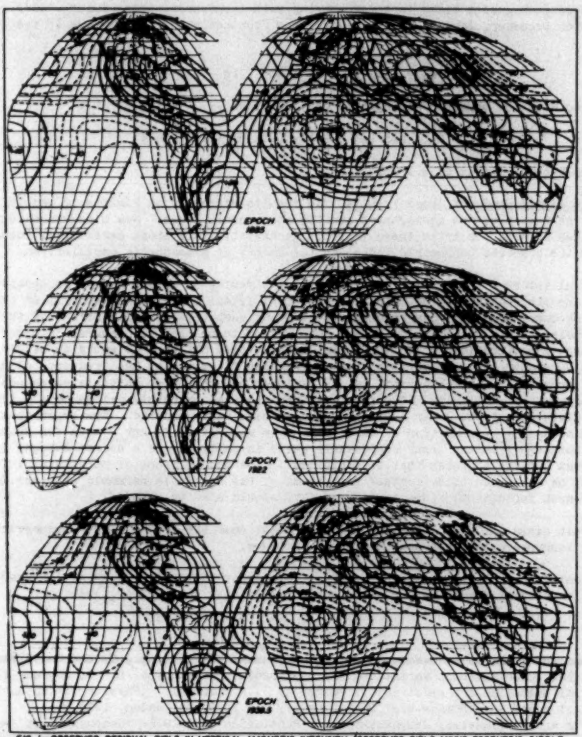

FIG. 1—OBSERVED RESIDUAL FIELD IN VERTICAL MAGNETIC INTENSITY (OBSERVED FIELD MINUS ECCENTRIC-DIPOLE FIELD); CONTOUR-INTERVAL 2000γ (2×10^{-4} CGS)

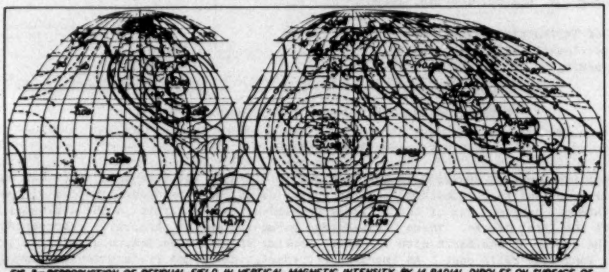

FIG. 2—REPRODUCTION OF RESIDUAL FIELD IN VERTICAL MAGNETIC INTENSITY BY 14 RADIAL DIPOLES ON SURFACE OF EARTH'S CORE AT LOCATIONS SHOWN BY ·, STRENGTH OF DIPOLES GIVEN IN 10^{25} CGS (+ INDICATES NORTH-SEEKING END DOWNWARD); CONTOUR-INTERVAL 2000γ (2×10^{-4} CGS)

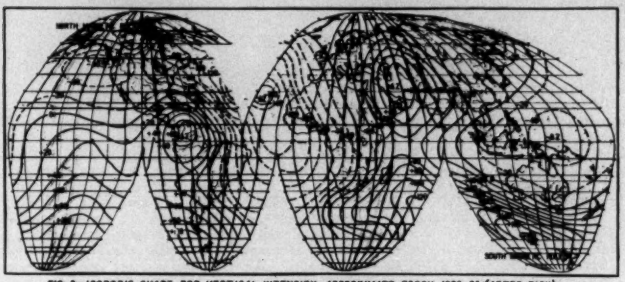

FIG. 3—ISOPORIC CHART FOR VERTICAL INTENSITY, APPROXIMATE EPOCH 1920-25 (AFTER FISK)
[POSITION OF ISOPORS IN HIGH LATITUDES, ESPECIALLY NEAR THE MAGNETIC POLES, VERY UNCERTAIN]

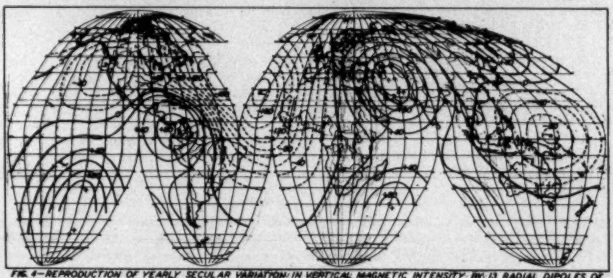

FIG. 4—REPRODUCTION OF YEARLY SECULAR VARIATION IN VERTICAL MAGNETIC INTENSITY BY 13 RADIAL DIPOLES OF UNIFORM STRENGTH (0.07 X 10^{25} CGS) ON SURFACE OF EARTH'S CORE AT LOCATIONS SHOWN BY • (+ INDICATES NORTH-SEEKING END DOWNWARD); CONTOUR-INTERVAL 20γ (2 X 10^{-4} CGS)

The strengths of both the centric and eccentric dipoles are the same, namely 8.1 × 10^{25} cgs units.

The eccentric dipole accounts for approximately 80 per cent of the observed magnetic field; the remaining 20 per cent or residual field requires a different representation. This residual field exhibits certain distinct characteristics--there are a number of "poles" where vectors of the magnetic force converge or diverge. These regions are well pictured on isodynamic charts of vertical intensity, each pole being at the center of a large oval nest of isodynamic lines of continental extent (Fig. 1).

Each of these nests of isodynamic lines may be approximately represented by the derivative with respect to r of a series of zonal harmonics of the form

$$a \sum_{0}^{\infty} (a/r)^{n+1} A_n P_n(\cos \theta)$$

where a = radius of Earth, r = radial distance, θ = angular distance from an arbitrarily chosen point near the center of the nest, P_n = the Legendre function of degree n, and A_n = an arbitrary constant. If the values of A_n are empirically determined for any particular nest of curves, a distribution of magnetic matter on the surface of any sphere with r less than a may be computed which would give rise to that nest of curves by means of the formula

$$a/4\pi \sum_{0}^{\infty} (2n + 1/n)(a/r)^{n+1} A_n P_n(\cos \theta)$$

When r is nearly equal to a, that is, when the hypothetical layer of magnetic matter is just beneath the Earth's surface, the convergence of the series is good, but as the series is evaluated for greater and greater depths the higher-order terms become increasingly important. At a depth

such that r = (a/2) the series can be closely represented by

$$A \sum_{0}^{\infty} (2n + 1)P_n(\cos \theta)$$

which is the Poisson sum and is identical with the spherical harmonic representation of a radially directed dipole at the surface of the sphere. In actual practice, of course, the infinite series could not be employed, the calculations being carried out for a finite series containing seven terms.

Having thus decided on a suitable depth, an attempt was made to represent the residual field for 1922 by appropriately disposed dipoles of suitable strength at the uniform depth a/2 (Fig. 2). Since some of the nests of curves are oval-shaped, the use of more than one dipole was necessary to reproduce the ellipticity in those cases. No appreciable effort was expended on selecting the strengths and locations of the dipoles so that the representation does not constitute the best that could be obtained by this metnod. Its highly suitable character is attested by the magnitude of the residuals which averages 1100Y, about four per cent of the average value of vertical intensity for the whole field of the Earth in the region investigated. (No attempt was made to fit the field in extremely high latitudes because of the notable uncertainty of values of vertical intensity for those regions.) The location of the isodynamic lines was accomplished graphically.

A similarity between the residual field and the annual secular-variation field [2] suggests that it likewise may be represented by dipoles at a depth (a/2) (see Fig. 3). Such a representation was attempted and found to be thoroughly satisfactory. In this case a further restriction could be imposed--all the dipoles could be of the same strength (Fig. 4). A cursory examination of the dipole-distributions for the residual field and the secular-variation field reveals that the two systems tend to be "orthogonal", that is, the secular-variation dipoles are close to the zero isodynamic lines of the residual field. The average value of the residual field in vertical intensity is 4400Y; the average value of the field where the secular-variation dipoles are located is 2500Y.

An interesting relationship is revealed when the magnitudes of the various dipoles are considered. The dipoles of the residual field average about 1/80 as strong as the centric or eccentric dipole and vary among individuals by a factor of 2.5. The secular-variation dipoles are about 1/100 as strong as those of the residual field so that if secular change were to continue for a century at the rate indicated for the epoch considered a new residual field would be built up of the same magnitude as that existing at present. It is of interest to note that all historic records of secular change suggest that it does not continue in the same direction and sense at any one place for more than a century or two, and that this generalization has been borne out by measurements of the connate magnetization of geological sediments [3].

Inspection of the residual field for the epochs 1885, 1922, and 1939.5 (the latter obtained by extrapolating the 1922 data by means of observatory-records) indicates that secular change is a change in the residual field consisting of changes in position, shape, size, and intensity of the various positive and negative areas of the residual field. No very appreciable part of secular change may be represented as a change in magnitude of either the centric or eccentric dipole.

Several clear inferences may be drawn from this representation of the permanent and secular-variation field by dipoles. It should not be thought that the dipoles themselves are real entities. Thus the centric or eccentric dipole may be thought of as an expression of a relatively uniform magnetization of the entire Earth, a spherical core of the Earth, or some spherical shell. No conclusions can be reached relative to the depth at which this uniform magnetization exists except that a thin spherical shell or a small central core could scarcely contain enough magnetic matter to produce the observed field. The dipoles of the residual field probably correspond to lenticular regions of magnetization between the surface of the Earth and the depth at which the dipoles are located. The depth (a/2) probably represents the lower limit to which these lenticular regions may extend, for if the surface effects were due to magnetization below this level extremely fantastic distributions of magnetization would have to be hypothesized to account for them. Nor can these lenticular regions of magnetization be located within the thin crust of the Earth with which geological studies acquaint us: Assuming that the intensity of magnetization in the region were one cgs unit per cc--a value several magnitudes greater than is observed for surface-rocks except in rare cases--the thickness of magnetic material near the center of one of these regions would have to be about 40 km.

Naturally, no implications as to the cause of these regions of magnetization or of the magnetization of the entire Earth are involved in the foregoing remarks, and it must be understood that when the term magnetization has been used it has been with the recognition that the effects could be produced by equivalent electric current-systems. This representation of the Earth's magnetism and its secular change by sets of dipoles is not presented as a theory of geomagnetism but as a set of facts and considerations to which any theory of geomagnetism must accommodate itself.

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NOTE ON SURFACE-FIELD ANALYSIS

E. H. Vestine

In a famour memoir Gauss [see 1 of "References" at end of paper] showed that the surface magnetic field of a sphere could be separated into parts of origin external and internal to the sphere, using the method of spherical harmonic analysis. This analysis also afforded a means of computing the field in adjacent regions of free space from a knowledge of the field over the surface of the sphere.

Neumann [2], Schmidt [3], Schuster [4], and others have introduced various improvements in the technique of spherical harmonic analysis and have thereby permitted the achievement of results important in the theory of geomagnetism. However, certain limitations of this valuable method have always been keenly in evidence. In such an analysis an infinite sequence of spherical harmonic terms is usually required to completely represent the field. In cases where the surface-field is of a type adequately represented by only a small number of spherical harmonic terms, so that those remaining may be neglected, the Gaussian method yields a very convenient and useful analysis. But it is sometimes found that the electric or magnetic surface-field is complicated and/or of a type expressed adequately only by many spherical harmonic terms. A spherical harmonic analysis may then become so laborious that it becomes futile from a practical point of view, although still possible in theory. This particular limitation of the Gaussian method often arises in geomagnetism, where complicated features appear not only in the Earth's general magnetic field but also in many of its additional surface-fields varying periodically and aperiodically in time.

The Earth and its atmosphere are electrically conducting. The Earth's interior and its outer atmosphere have a much higher electric conductivity than the air near the ground. Since the Earth's magnetism varies with time, contributions of origin, both external and internal to the Earth's surface, appear in its measured surface-magnetic fields. A natural and fundamental first stage in the analysis and study of such fields is thus usually the determination of their parts of external and internal origin. Having effected this separation, the continuation of the surface-values of the field into regions of space adjacent to the Earth's surface may be needed. Finally, the external and internal parts of the field are sought in terms of spacial distributions (real or probable) of neighboring electric currents or magnetic matter, using additional considerations of a non-magnetic character and in some cases the behavior of continuations of the field within the space near the Earth's surface.

The foregoing problems can be formulated in somewhat different but more general terms. Thus field-analysis in the case of the Earth may involve some or all of the following problems:

(1) Given the tnree orthogonal components of the magnetic force over a closed surface S, determine their parts of external and internal origin.
(2) Calculate the potential-function regular throughout all space external (or internal) to S, conforming to the prescribed surface-values of the potential (problem of Dirichlet) or to its normal derivative (problem of Neumann).

(3) Obtain a continuation of the potential or its normal derivative on S for regions regular near S but not regular throughout the entire space inside or outside S (problem of Cauchy).
(4) Estimate the spacial distributions of magnetic matter or electric current near S, or the strengths of single or double distributions of magnetic matter (or current) on specified closed surfaces external or internal to S which could give rise to the observed parts of external and internal origin on S.

It will in general be supposed that the potential and its first and second space-derivatives are continuous along and on crossing S.

A method based on representation of the field on S by spherical harmonics frequently permits the solution of these problems. However, the spherical harmonic analysis of the somewhat complex surface-fields of geomagnetism often entail much labor, especially in cases where we do not find it practical to assume symmetry of the field about some central axis or great circle of the sphere. The computations also become additionally complicated when the ellipticity of the Earth is taken into account. It is therefore desirable to inquire into more general methods involving the use of powerful techniques of numerical or machine procedures, but it is first instructive to review the methods of analysis based on analytic representations of surface-fields from a standpoint perhaps more fundamental than that customarily adopted.

When using analytical representations of the field the analysis is accomplished by fitting appropriate particular solutions of Laplace's equation

$$\Delta V = 0 \tag{1}$$

where V is the magnetic potential, to the observed surface-values of the field.

Whittaker [5] has shown that the general solution of Laplace's equation is

$$V(x, y, z) = \int_{-\pi}^{\pi} f(z + ix \cos u + iy \sin u, u)\, du \tag{2}$$

where f is an arbitrary function of u and x, y, z, differentiations under the sign of integration being permissible. It is the three-dimensional analogue of

$$V = g(x + iy) + h(x - iy) \tag{3}$$

the general solution of

$$(\delta^2 V/\delta x^2) + (\delta^2 V/\delta y^2) = 0 \tag{4}$$

in two dimensions. Every solution of Laplace's equation analytic throughout the interior of some sphere is expressible by an integral of the form (2).

As examples of particular solutions derivable from (2) consider those used in spherical harmonic analysis

$$\left.\begin{aligned} &\int_{-\pi}^{\pi} (z + ix \cos u + iy \sin u)^n \cos mu\, du \\ &\int_{-\pi}^{\pi} (z + ix \cos u + iy \sin u)^n \sin mu\, du \end{aligned}\right\} \tag{5}$$

where n and m are integers such that $0 \leq m \leq n$. If $x = r \sin\theta \cos\varphi$, $y = r \sin\theta \sin\varphi$, $z = r \cos\theta$, and $\psi = u - \varphi$, then

$$\left.\begin{aligned} &\int_{-\pi}^{\pi} (z + ix \cos u + iy \sin u)^n \cos mu\, du \\ &\quad = r^n \cos m\varphi \int_{-\pi}^{\pi} (\cos\theta + i \sin\theta \cos\psi)^n \cos m\psi\, d\psi \\ &\quad = \frac{2\pi i^m n!}{\sqrt{a_n^m}\,(n+m)!}\, r^n P_n^m(\cos\theta) \cos m\varphi \end{aligned}\right\} \tag{6}$$

where $a_n^0 = 1$, and $a_n^m = 2(n-m)!/(n+m)!$ for $m \geq 1$. The second integral of (5) gives

$$\frac{2\pi i^m n!}{\sqrt{a_n^m}\,(n+m)!}\, r^n P_n^m(\cos\theta) \sin m\varphi \tag{7}$$

where

$$P_n^m(\cos\theta) = \frac{\sin^m\theta\, d^{n+m}}{2_n^n\,!\,(d\cos\theta)^{n+m}}(\cos^2\theta - 1)^n \sqrt{a_n^m} \qquad (8)$$

the normalized spherical harmonics of Schmidt [3].

We may use this result to obtain the solution appropriate to a surface-field of the Earth, in the case where the field consists of parts originating both above and below the Earth' surface. We have the general theorem that if G (x, y, z) is any function which satisfies $\Delta G = 0$, the function $\frac{1}{r} G\left(\frac{x}{r^2}, \frac{y}{r^2}, \frac{z}{r^2}\right)$ also satisfies the same differential equation. Corresponding to any surface harmonic $g_n(\theta, \varphi)$ there thus correspond two solid harmonics $r^n g_n(\theta, \varphi)$ and $r^{-n-1} g_n(\theta, \varphi)$. Using (6) and (7) and including the solution obtained by replacing r^n by r^{-n-1} we obtain a particular solution appropriate to a surface potential consisting of parts V_e and V_i, respectively, of origin external and internal to the spherical surface r = a, as in (9).

$$V = a \sum_{n=0}^{\infty} \sum_{m=0}^{n} [(r/a)^n E_n^m \sin(m\varphi + \epsilon_n^m) + (r/a)^{-n-1} I_n^m \sin(m\varphi + i_n^m)] P_n^m(\cos\theta) \qquad (9)$$

Here the constants E_n^m, ϵ_n^m and I_n^m, i_n^m correspond to V_e and V_i, respectively. The expression simplifies for the case r = a, since then (r/a) = 1.

In the applications to geomagnetism the coefficients E_n^m, ϵ_n^m, I_n^m and i_n^m are obtained from the tangential and radial magnetic force at r = a, using the additional relation for the force

$$F = -\operatorname{grad} V \qquad (10)$$

A separation of the surface-values of F into parts of external and internal origin, and the calculation of V and its space-derivatives in adjacent regions of free space can usually be effected when the constants of (9) are determined.

A solution for V in terms of the function $P_n^m(\cos\theta)$ is unique. However, a wide range of other particular solutions may be obtained from (2) in terms of other functions appropriate to the surface-boundary conditions; their utility will in general tend to increase as the number of terms needed to express the surface-field diminishes. It thus appears that other particular solutions of (2) may be useful in analyzing certain special types of fields requiring many spherical harmonic terms in an adequate analytic representation. Their utility seems likely to be enhanced when the type of field shows symmetrical features relative to certain axes, planes, or great circles of the sphere, in the locations of their maxima and minima in V. If these special properties of the field do not exist it is unlikely that other functions will facilitate an analysis of the field, when spherical harmonic functions are unsatisfactory. An analysis based on analytic representations of given arbitrary functions on a boundary-surface is also likely to be simplified by choosing the functions most naturally associated with the geometry of this surface, and these functions are spherical harmonics in the case of the sphere. A procedure not yet tried but which should give some measure of success in special cases would be that of grouping infinite sequences of spherical harmonic terms with known coefficients, and then evaluating constant coefficients for each of these terms consisting of separate infinite series. The particular solutions of Laplace's equation appropriate to a plane can also sometimes be used over sufficiently small areas of a spherical surface in obtaining an approximate analysis (6). We next consider a new and very powerful method of analysis which avoids the use of analytical representations of the field. In the present note we shall confine our discussion to the problem of separation of the potential of the field into external and internal parts.

Consider a region v enclosed by a surface S (Fig. 1) in which there are bodies of magnetic matter M_i. Suppose there are also bodies of magnetic matter M_e in the region outside S. Let V_i and V_e be the magnetic potentials due to M_i and M_e, respectively, their combined potentials being equal to V on S. We require the values V_i and V_e separately from a knowledge of V and $\delta V/\delta n$ on S.

If U and V are any two functions with continuous first space-derivatives in the region (v + S) and having continuous second space-derivatives in the volume v, we have Green's theorem

$$\int_v (U\,\Delta V - V\,\Delta U)\,dv = \int_S [U(\delta V/\delta n) - V(\delta U/\delta n)]\,dS \qquad (11)$$

where n refers to the outward normal. If we write U = (1/r), where r is the distance from a fixed point P outside S to a variable point Q on S

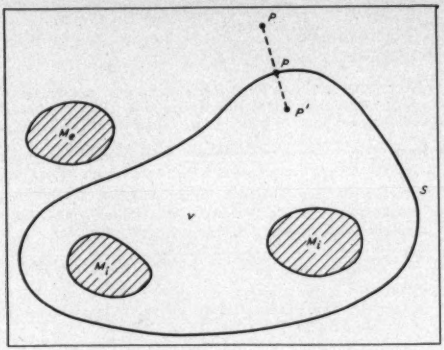

FIG. 1

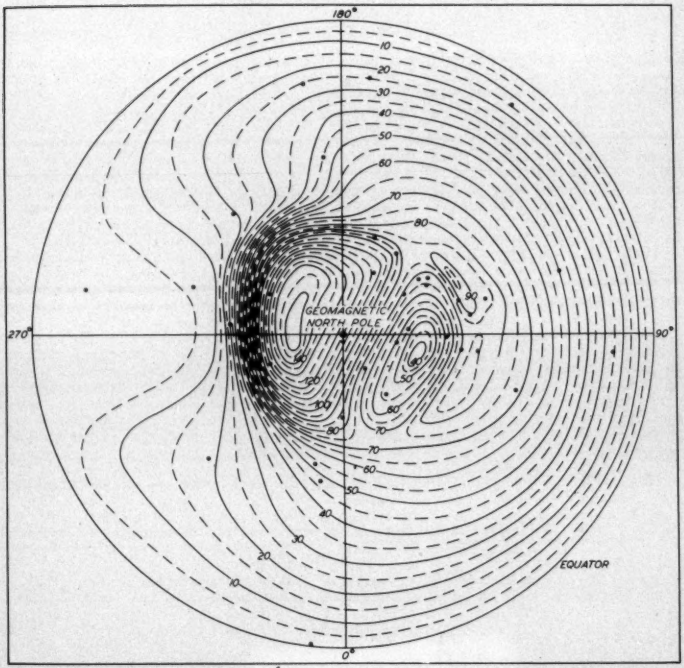

FIG. 2—EQUIPOTENTIALS, IN UNITS OF 10^4 CGS, OF MEAN HOURLY SURFACE-FIELD OF MAGNETIC STORM AT 16^h GMT, MAY 1, 1933, ESTIMATED (APART FROM A CONSTANT) FROM HORIZONTAL INTENSITY, NORTHERN HEMISPHERE, ASSUMING SYMMETRY ABOUT GEOMAGNETIC EQUATOR

$$\int_V [(\Delta V/r) - V\,\Delta(1/r)]\,dv = \int_S [\delta V/r\delta n - V\delta(1/r)/\delta n]\,dS$$
$$= \int_S \Delta V_i\,dv/r = -4\pi V_i(P)$$

Thus

$$V_i(P) = -(1/4\pi)\int_S [\delta V/r\delta n - V\delta(1/r)/\delta n]\,dS \qquad (12)$$

giving V_i at P in terms of V and $(\delta V/\delta n)$ on S. In the same way it may be shown that

$$V_e(P') = (1/4\pi)\int_S [\delta V/r\delta n - V\delta(1/r)/\delta n]\,dS \qquad (13)$$

where P' is a point anywhere within the closed surface S.

Suppose P and P' approach the same point p on S in a normal direction. We consider the limiting values attained by V_i and V_e as P and P' approach p. The values $V_i(P)$ and $V_e(P')$ of (12) and (13) may be regarded as due to a single distribution plus a double distribution of magnetic matter on S, in thin layers, and of strengths $\sigma = -(1/4\pi)(\delta V/\delta n)$ and $\mu = (1/4\pi)V$, respectively. As the point P external to S approaches S along the normal at the point p, the single distribution yields a contribution approaching the value

$$-(1/4\pi)\int_S (\delta V/r\delta n)\,dS$$

and the value approached for the double distribution is

$$(1/4\pi)\int_S [V\delta(1/r)/\delta n]\,dS + 2\pi\mu(p) = (1/4\pi)\int_S [V\delta(1/r)/\delta n]\,dS + V(p)/2 \qquad (14)$$

the potential of a single distribution being continuous and that of a double distribution discontinuous by an amount $4\pi\mu$ in crossing S. If η is a small area surrounding the point p, which we allow to shrink to zero in the limit, (13) and (14), respectively, become

$$V_i(p)_+ = -(1/4\pi)\int_S [\delta V/r\delta n - V\delta(1/r)/\delta n]\,dS + V(p)/2 \qquad (15)$$

$$V_e(p)_- = (1/4\pi)\int_S [\delta V/r\delta n - V\delta(1/r)/\delta n]\,dS + V(p)/2 \qquad (16)$$

Subtracting (15) from (16) we infer that at the point p

$$(V_e - V_i) = (1/2\pi)\int_S [\delta V/r\delta n - V\delta(1/r)/\delta n]\,dS \qquad (17)$$

Using the additional relation $V = (V_i + V_e)$ and (17) we hence find V_i and V_e from a knowledge of V and $(\delta V/\delta n)$ at all points on S. In a somewhat similar way, we may calculate the normal derivatives of V_i and V_e at the point p.

In the event that $(\delta V/\delta n)$ is known but V is known only apart from a constant over S, (17) permits the calculation of $(V_e - V_i)$ apart from a constant. This information is sufficient to determine the component of - grad $(V_e - V_i)$ tangential to S.

The interesting theorem expressed by (17) applies to any closed regular surface. In the case of a sphere of radius a, taking the point p as pole of spherical coordinates a, θ, φ we have

$$[V_e(p) - V_i(p)] = (1/2\pi)\int_0^{2\pi}\int_0^{2\pi} [2a(\delta V/\delta n) + V]\cos\psi\,d\psi\,d\varphi \qquad (18)$$

where $\psi = 0/2$. If $(\overline{\delta V}/\delta n)$ and $\overline{V}$ are the mean values of $(\delta V/\delta n)$ and V, respectively, along parallels of latitude, we may rewrite (18) in the form (19).

$$[V_e(p) - V_i(p)] = \int_0^{\pi/2} [2a(\overline{\delta V}/\delta n) + \overline{V}]\cos\psi\,d\psi \qquad (19)$$

Thus the problem of computing the difference $(V_e - V_i)$ at any point p on the surface of a sphere reduces to that of the numerical or graphical evaluation of integrals of the form (19). It may also prove practical to compute such integrals by means of a simple mathematical machine.

In exploring the possibilities of the method, an analysis was made of the geomagnetic disturbance-field for 16^{h} GMT, May 1, 1933, a time of magnetic storm. The lines of equal V and $(\delta V/\delta n)$ (Figs. 2 and 3) were roughly estimated and drawn on plane maps of the Northern Hemisphere, assuming the same distributions with opposite sign for the Southern Hemisphere. A series of nine nets were drawn on celluloid giving the curves of equal θ and φ, for positions of the point p at 10° intervals of geomagnetic latitude. To obtain $(V_e - V_1)$ at a given point p, the appropriate net was placed in turn over the maps for V and $(\delta V/\delta n)$, and the values $(\delta V/\delta n)$ and V were obtained. These values were next plotted graphically to obtain the integral of (19). The average computing-time required per point p was about one hour.

The ratios (V_e/V) at the points p computed up to the present vary from about 0.5 to 0.8, and it has been thought worth while to include these incomplete results here as a matter of interest. Except near the auroral zones, about 60 per cent of the observed field appears to be of external origin. Near the auroral zones, greater variability is shown. An analysis involving the disturbance daily variation of storms has not hitherto been attempted because of the formidable difficulties involved in the use of spherical harmonics for this type of field, but it appears that results commensurate with the accuracy of the data have been attained by the use of the foregoing simple integral method. A more detailed account of the analysis of fields by integrals including further consequences of the theory will be presented for publication in the Journal of Terrestrial Magnetism and Atmospheric Electricity.

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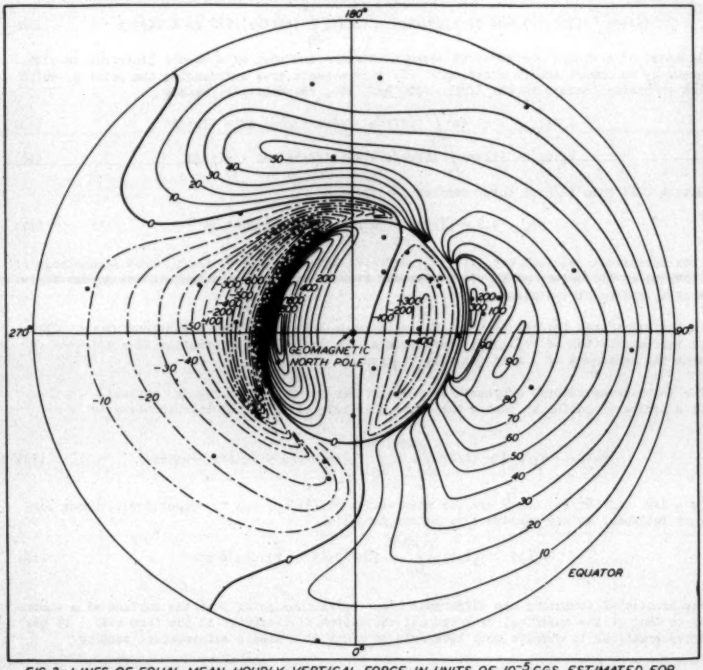

FIG. 3—LINES OF EQUAL MEAN HOURLY VERTICAL FORCE, IN UNITS OF 10^{-5} CGS, ESTIMATED FOR MAGNETIC STORM AT 16^{h} GMT, MAY 1, 1933

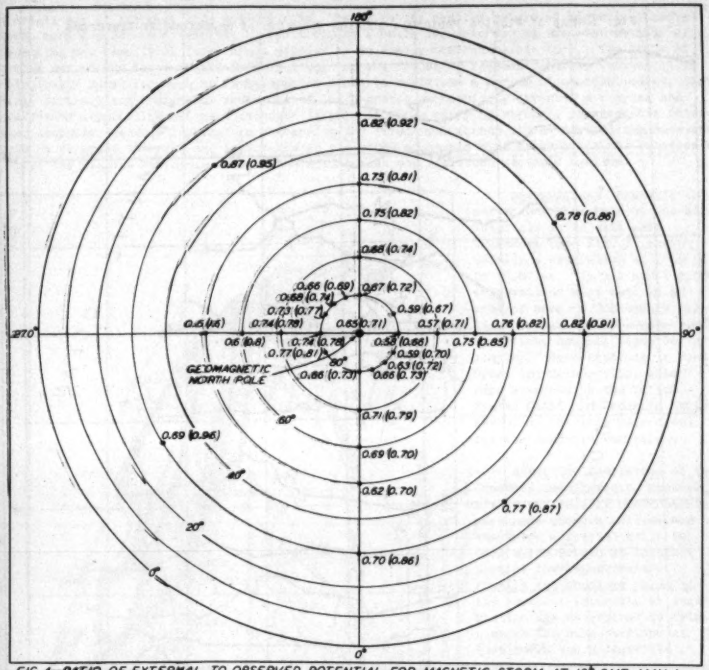

FIG. 4—RATIO OF EXTERNAL TO OBSERVED POTENTIAL FOR MAGNETIC STORM AT 16h GMT, MAY 1, 1933, NORTHERN HEMISPHERE; COMPUTED VALUES, IN PARENTHESES, NEGLECT FIELD IN SOUTHERN HEMISPHERE

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MAGNETIC STUDIES OF THE FLORIDA PENINSULA

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(Published with the approval of the Director, U. S. Geological Survey)

(Abstract)

Introduction--This investigation was undertaken primarily as a pilot-experiment for gaining information concerning the field-technique and accuracy which is needed for covering large areas

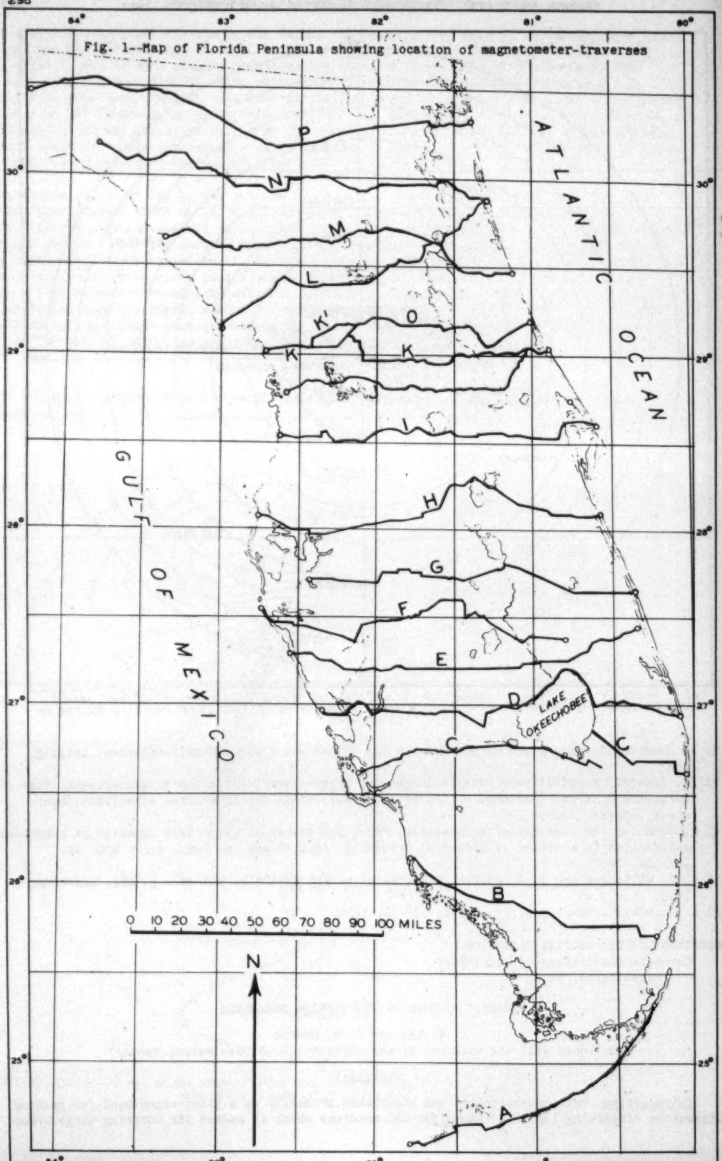
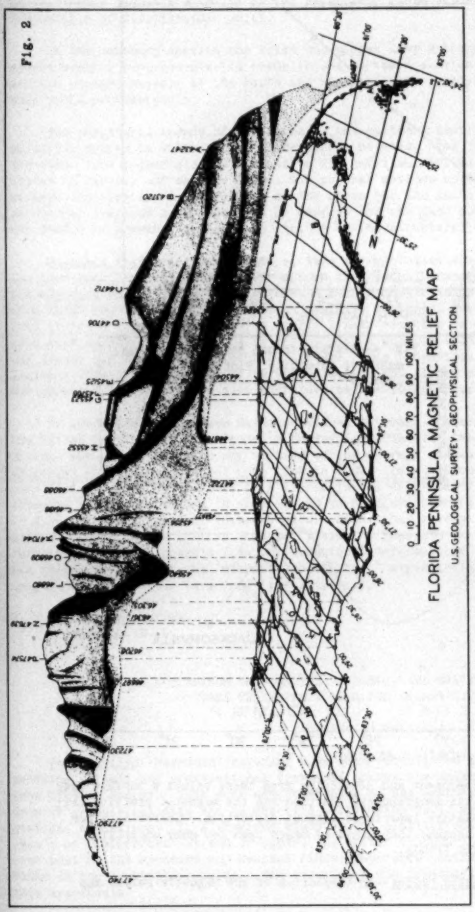


Fig. 1--Map of Florida Peninsula showing location of magnetometer-traverses

in detail and at the same time economically. Owing to the complex nature of magnetic observations, such a pilot-study serves, in addition, as a basis for determining the best methods of presenting the results of large areal studies in an easily comprehensible form. The State of Florida was chosen for such preliminary study for the following reasons: First, because it is geologically ideal for such an investigation since it comprises a series of unconsolidated, flat-lying, Tertiary and Cretaceous sediments of low magnetic permeability covering a complex and much-folded crystalline basement composed largely of rocks carrying strongly paramagnetic materials; secondly, because information concerning the structural trends of the crystalline basement would be of great interest and importance in the study of Appalachian orogeny and the relationship of the Florida Peninsula to both the Appalachian and Antillean tectonic systems.

Fig. 2



Observations--Magnetic observations were made at one-mile intervals on 16 east-west traverses (see Fig. 1) having usually a separation of from 20 to 40 miles. In all about 2,300 observations were made in an area of some 50,000 square miles. All observations were made with a vertical Askania magnetic variometer. Base-stations at Fort Myers and Gainesville, which were measured by the United States Coast and Geodetic Survey, served as absolute references for the magnetic variations.

After the completion of the traverse measurements, special tie-in and recheck measurements were made using a null-method employing a special built-in coil which formed an integral part of the magnetometer. Finally the absolute value of the vertical intensity at each station was determined in relation to the base-stations at Fort Myers and Gainesville.

It is estimated that errors between successive stations are of the order of from three to five gammas. The accuracy of the base-station measurement is of the order of $\pm$ 10 gammas. The difference between the two base-stations as determined from the traverse measurements agreed within 50 gammas with the difference as measured by the United States Coast and Geodetic Survey. Combining all these factors it is thought that the absolute value of the vertical magnetic intensity at any one station as here computed may be in error by an amount of the order of 100 gammas. The difference in values between successive stations are, however, as noted above, accurate to a much greater degree.

Charting of magnetic values--It was found that by using the

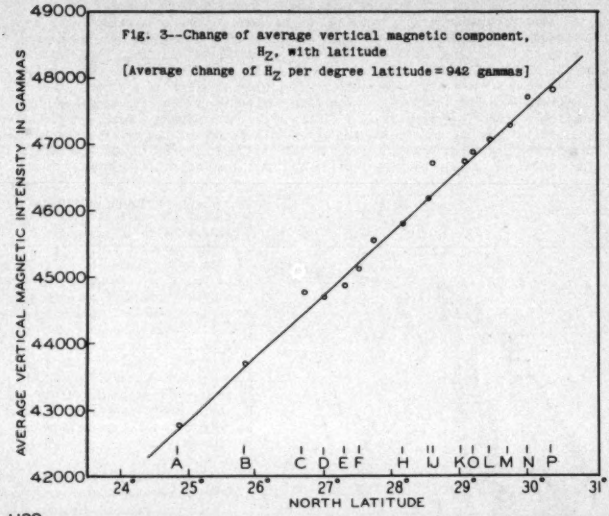


Fig. 3--Change of average vertical magnetic component, H_Z, with latitude
[Average change of H_Z per degree latitude = 942 gammas]

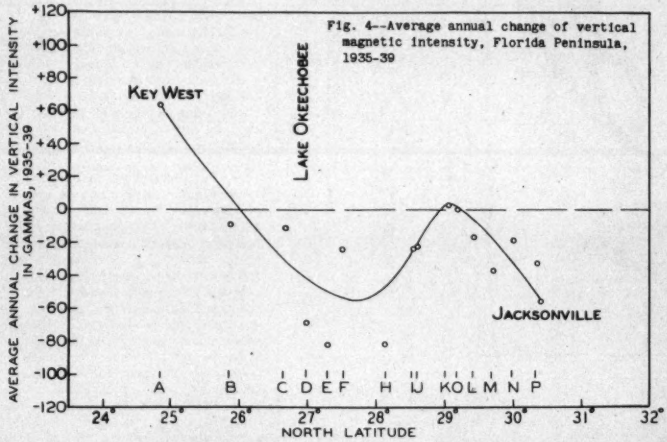


Fig. 4--Average annual change of vertical magnetic intensity, Florida Peninsula, 1935-39

actual values of the vertical magnetic component and developing from these values a surface (see Fig. 2), which is directly dependent on the geographical position and the magnetic profiles, all magnetic features will maintain their relative importance without distortion. Corrections for latitude and longitude were not applied because they would be based upon too many uncertain factors and would conceal general geologic trends.

Geological features related to magnetic relief--An inspection of the magnetic relief-map

(Fig. 2) reveals a series of magnetic ridges and valleys, part of which correspond to topographic features in the crystalline basement and part to stratigraphic variations in the magnetic permeability of the basement-rocks. On the basis of the magnetic relief the area is seen to be divided into three sections: A northern section extending southward to a line approximately through Kissimmee and St. Petersburg; a central section lying between Kissimmee and Lake Okeechobee; and a southern section extending from Lake Okechobee to Key West.

In the northern section a series of folds and ridges are indicated having trends of approximately north 42° to 44° east. The magnetic values decrease to the west and south so that both the folds and the crystalline basement as a whole are plunging to the southwest in this area. Certain minor magnetic wrinkles on the relatively large folds may reflect differences in mineral composition of stratigraphic units.

In the southern section the folds and ridges have a trend of north 45° to 46° west, lying almost exactly perpendicular to those in the northern section. The basement as a whole in this section plunges steeply to the south and somewhat more gently to the west. The general slope is thus again southwesterly.

The structural trends of the folds in the northern section parallel the trend of the Appalachian system to which they are presumably related. The trends of the southern section on the other hand appear closely related to the Antillean system, as they are parallel to structural trends in central and eastern Cuba. The central section appears to be transitional in character between the Appalachian structures on the north and the Antillean trends on the south. The structural features here appear to be complex and the data obtained in the present survey are too meagre to present any adequate picture of the structural conditions in this section.

Magnetic features--The results of this survey indicate that local geologic bodies in Florida introduce variations which over-shadow the gradual changes due to latitude. By averaging the magnetic values along each traverse a mean magnetic value for that traverse may be obtained. When these mean values of the vertical magnetic component are charted against the mean geographical latitude for each traverse, a nearly linear relation is observed as seen in Figure 3. For such mean magnetic values there is essentially a uniform increase from south to north of about 942 gammas per degree of geographic latitude. The proportion of this change due to the magnetic-latitude effect may be shown to be approximately 450 gammas per degree, leaving a remainder of 490 gammas per degree which must therefore be due to geologic factors.

By comparing the average magnetic values for each traverse as determined from the data of the United States Coast and Geodetic Survey for 1935 with the average value obtained in the present survey, an estimate may be made of the average annual change of the vertical magnetic component during the interval from 1935 to 1939. These values are shown in Figure 4 and indicate that the vertical component is increasing in value along the Florida Keys and along the K-traverse but is decreasing in central and in northern Florida. At this time it is not possible to give the exact cause of these changes. Since they reverse in sign, they cannot be due to any general change in the Earth's magnetic field. A possible explanation may be found in deep-seated magmatic movements, plastic flow, or structural deformation. For this reason magnetic methods may serve, so to speak, as "microscopes of time," since geologic evidences of such changes can only be observed after very long time-intervals.

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A COMPARISON OF MAGNETIC, SEISMIC, AND GRAVITATIONAL PROFILES ON THREE TRAVERSES ACROSS THE ATLANTIC COASTAL PLAIN

George P. Woollard

Introduction--Magnetic traverses have been established by the writer along the lines of existing seismic and gravitational traverses across the Coastal Plain of Virginia and New Jersey (see Figs. 1 and 2). This work was undertaken to see what relations existed between these three sets of geophysical data and to see if a correlation could be made between them and subsurface geologic conditions. In a previous study of the gravitational anomalies observed in Virginia [see 1 of "References" at end of paper] the writer reached the conclusion that the anomalies over most of the Piedmont and Coastal Plain areas were controlled primarily by lithologic variations in the crystalline rocks. The results of the present investigation appear to substantiate this hypothesis.

In New Jersey the line of the Barnegat Bay seismic-gravitational traverse [2] was followed and the magnetic stations were established at intervals of approximately one-half mile. On the Cape May seismic-gravitational traverse [3] in the southern part of the State an interval of about seven-tenths of a mile was used between magnetic stations. This change of spacing was made because it was observed on the Barnegat Bay traverse that the closer spacing was not needed to indicate clearly the variations of the magnetic field. Both of these magnetic traverses consist of a single line of measurements except that on the Barnegat Bay traverse the western extremity was expanded into a network of stations at a quarter-mile interval along roads covering a strip ten miles wide. This was done in order to depict complicated geologic structural conditions in the Triassic material underlying this part of the Coastal Plain.

In Virginia two magnetic traverses were established along the line of the Cape Henry seismic-gravitational traverse [4]. One was made on the north side of the James River from Richmond to Fortress Monroe, and the other on the south side of the James River from Centralia to Virginia Beach and Cape Henry. On the southern traverse a magnetic station spacing of seven-tenths of a mile was used and on the northern traverse a spacing of approximately a mile was used. These two magnetic traverses were desirable since the existing seismic and gravitational line crosses the James River twice.

In order to check the strike of a large positive anomaly-anomaly area appearing on both these magnetic traverses a third traverse across the Coastal Plain was run from Petersburg to Waverly, Virginia, using a station-interval of a mile.

As it was desirable to know the magnetic behavior of the formational units that might compose the crystalline complex underlying the Coastal Plain, a fourth magnetic traverse was established across the Piedmont Province between Richmond and Charlottesville where the Coastal Plain basement-formations are exposed at the surface.

Method of survey--In conducting the magnetic investigations an Askania vertical-component magnetometer was used with a scale-sensitivity of 21.9 gammas. In Virginia all readings were made relative to an arbitrary base established near Centralia, Virginia, and in New Jersey an arbitrary base was used at Princeton for the Barnegat Bay traverse and another at Swedesboro for the Cape Bay traverse.

The survey was conducted in accordance with the standard method for measuring the vertical component of the Earth's magnetic field and since only one instrument was available, the survey was carried forward from a series of auxiliary base-stations tied to the master base-station. The determination of the diurnal variation of the Earth's magnetic field was made once every two hours by returning to a base-station common to two of the traverse-legs and in this manner the change in the general field of the Earth was noted. The field-data obtained were reduced for temperature-variation effects on the instrument, the observed diurnal variation in the Earth's magnetic field, and for changes in magnetic latitude along the line of traverse.

Acknowledgments--In carrying out the field-work for the magnetic investigations the writer wishes to acknowledge the personal aid extended by Meridith Johnson, State Geologist for New Jersey, who accompanied the writer on both magnetic traverses in New Jersey, and also the cooperation of the New Jersey Department of Conservation in supplying the maps needed for the survey. On the more detailed magnetic investigations in the vicinity of Princeton the writer is indebted to his wife, Eleanore Woollard, without whose aid this part of the work could not have been completed.

In Virginia the writer would like to express his appreciation for the helpful cooperation of the entire staff of the Geological Survey and to Dr. Bevan in particular for the many courtesies which made this part of the investigation possible. To Dr. Edmundson of the Virginia Geological Survey, who accompanied the writer in the field, thanks are due for many personal favors and assistance in carrying out every phase of the work.

To the National Research Council Fellowship Board the writer is indebted for a fellowship under whose tenure these investigations were made.

Historical background--Variations in seismic velocity for the basement crystalline rocks from 12,290 feet per second to 20,830 feet per second were noted by Ewing, Crary, and Rutherford [4] on their seismic traverse from Camp Lee to Cape Henry, Virginia, and although no attempt was made to assign these velocity-variations to specific rock-types, it was suggested by Miller [5] that the low-velocity values might represent Triassic sediments rather than the crystalline complex immediately underlying that portion of the Coastal Plain.

In his paper on the gravity-anomalies observed along the same traverse, Swick [6] called attention to a marked gravity "high" which occurred over an area in which Ewing's seismic depth-measurements showed no measurable relief in the basement-surface, and it was on the basis of these data plus similar observations on the Barnegat Bay traverse that the writer [7] first postulated a lithologic control of the observed gravitational and seismic velocity-variations in these areas.

Specific gravity-studies of the lithologic units composing the exposed "basement"-complex in the Piedmont area plus corrections applied to the observed gravity-anomalies for the overlying Coastal Plain sediments [1] showed, in the light of the seismic basement-configuration, that a lithologic control of the gravity-anomalies was quite probable over most of the Coastal Plain area. This qualification had to be introduced to take into consideration a marked gravity-depression, for the most part lying well out on the Continental shelf, which is imperfectly understood, and whose effect encroaches on the land area by variable amounts. In New Jersey the effect of this gravity-trough is relatively small, but in Virginia from Newport News out, it masks local effects that can be ascribed to either basement-surface variations or changes in the basement-lithology.

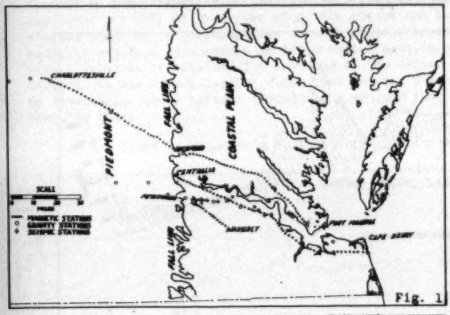

Fig. 1

The fact that the variations in seismic velocity observed in New Jersey [2 and 3] and in Virginia were similar and that there was agreement in the position of the high-velocity areas with the high gravity-anomaly areas, and conversely of the low-velocity areas with the gravitational "lows", particularly on the Barnegat Bay traverse, prompted the magnetic work herein described in order to see if an additional correlation with these data could be obtained. With the three sets of different data it was hoped that a unique solution as to cause might be obtained.

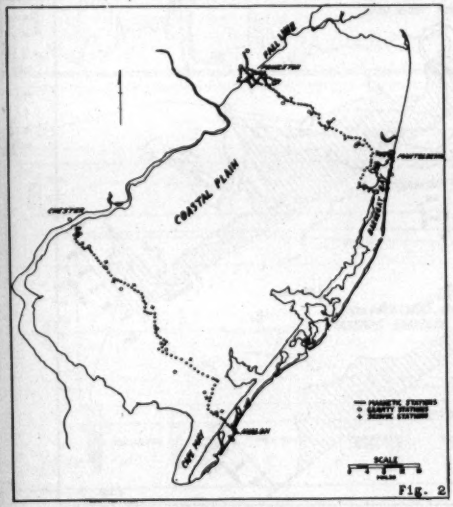

Fig. 2

Virginia Area--In Figure 1 are shown the lines of magnetic measurements established in Virginia and also the positions of the various seismic and gravitational stations in the areas adjacent to the magnetic stations. Three magnetic lines lie wholly in the Coastal Plain and a fourth, really an extension of the Fort Monroe - Richmond line, extends across the Piedmont to just beyond Charlottesville. This latter, as has been pointed out, was established to aid in interpreting the results obtained from the Coastal Plain traverse.

On all three traverses in the Coastal Plain a marked magnetic low exists near the Fall Line over areas which, from the available well data, appear to be underlain by granite. A marked area of magnetic "highs" about eight miles wide, however, occurs just to the east of this zone and these lie in the same area which is characterized by high basement-seismic velocity and also high gravitational values. The areas of magnetic "lows" near the Fall Line occupy the positions of low-gravity anomalies and low basement-seismic velocities. The change

between the two areas for the three sets of data are from 12,290 feet per second to 20,830 feet per second for the basement seismic velocity as measured at the Camp Lee and Prince George Seismic Stations; -19 to +12 milligals as measured at gravity-stations Nos. 700 and 703, and an average change of about 800 gammas on the magnetic values over the same area. The locations of these points and the vertical-intensity variation along the Coastal Plain magnetic traverses are shown in Figure 3. The exact character of the magnetic high appears to vary somewhat on the individual traverses, and the fact that it plots no regular curve is believed to be a reflection of marked local variations in the rock itself, since the depth of burial here is about 400 feet. That the high anomaly-area is probably a continuous feature over a large area, is indicated by its relatively constant width on the three traverses which cover a section about 20 miles along the strike. That the magnetic-anomaly variation is due to litnology and not subsurface basement-relief is indicated by the following seismic elevations obtained over the area in question: Camp Lee, 230 feet; Young Bloods Store, 260 feet; Prince George, 320 feet; Newville, 300 feet; Brandon, 300 feet. On the basis of known magnetic susceptibilities for various rocks it would appear that the rocks giving rise to the observed high magnetic anomalies might be similar to a gabbro or basalt. Such rocks are known to occur in the Wissahickon gneiss lying to the west of the Petersburg granite, which is the basement-rock at the Fall Line, but such an extensive band as the

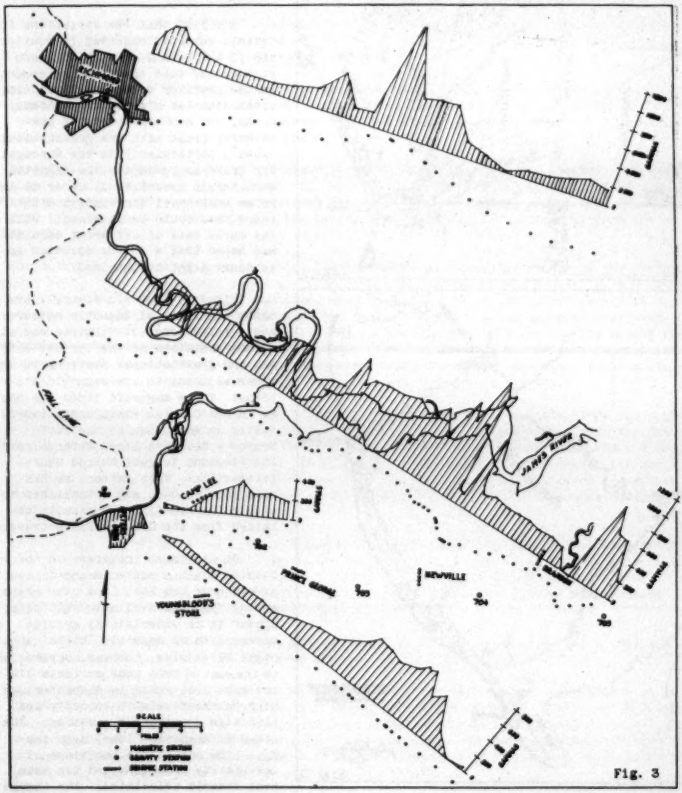

Fig. 3

one indicated beneath the Coastal Plain is not known.

The physical values for a gabbroic or basaltic rock are approximately: Density, 2.8 - 3.15; velocity, 21,000 feet per second; magnetic susceptibility, 3,300; observed surface magnetic vertical-intensity variation, 1,000 gammas.

The possibility of the correctness of Miller's suggestion [5] that the low seismic-velocity areas, which are also characterized by low magnetic and gravitational values, may represent Triassic material therefore appears bolstered, since diabase which has similar properties to those listed above is commonly found in the Triassic sedimentary basins. Objections to this hypothesis, however, are: (1) That conversations with the local drilling companies indicate that all known wells in the low-velocity area have penetrated typical Petersburg granite;(2) where Triassic sediments beneath the Coastal Plain as at Bowling Green, Virginia, have been drilled into, they have been recognized as such and not confused with the crystalline rocks (presumably the presence of similar material near Petersburg would have been noted); (3) the low magnetic values carry over 30 miles back into the Piedmont on the granites and granite gneisses; (4) the low gravity-anomaly values also persist over the granites of the Piedmont; (5) that if the gabbro-type rock were Triassic diabase it would be the widest continuous exposure known in the Atlantic area since all described exposures are only of the order of a mile across the surface-outcrop; (6) that if sediments and diabase occurred in juxtaposition to each other a marked change in elevation of the two surfaces would be expected as a result of differential erosion on the two materials of unequal hardness. Such a relation is obtained for instance on the buried extension of the Palisades Diabase Sill beneath the New Jersey Coastal Plain; the seismic depth-measurements in Virginia, though, show an essentially level surface indicating a uniform rate of erosion for both the low- and high-velocity areas.

In the light of these data it therefore appears that the low magnetic, low gravity, and low

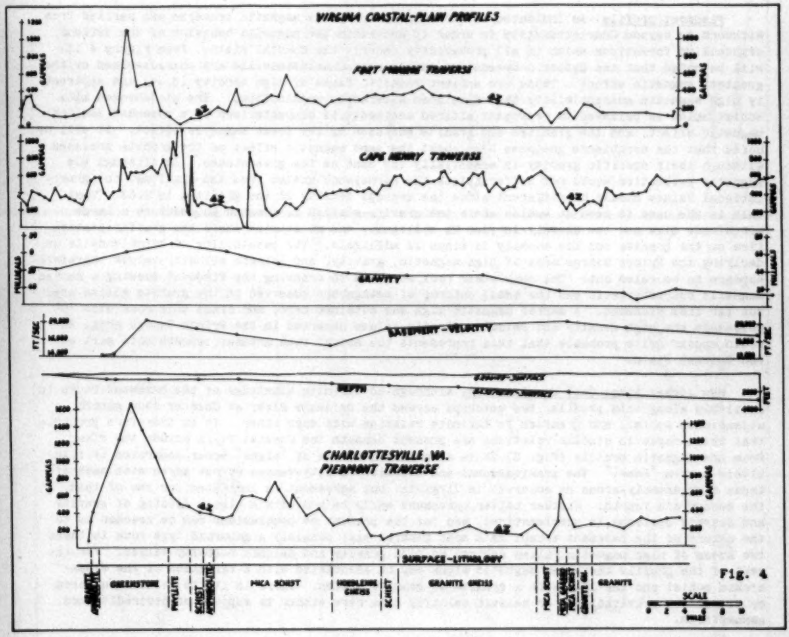

Fig. 4

seismic-velocity area does not represent a non-crystalline rock, and the available data do indicate the presence of a granite. The objection to this hypothesis is that surface velocity-measurements on granite show them to be characterized by a velocity of about 17,000 feet per second rather than 13,000 feet per second as observed at Camp Lee and Youngbloods Store. A possible explanation, however, may be that the porphyritic granites as seen near Petersburg have a lower modulus of elasticity and hence lower velocity-values as a result of their large grain-size and also larger shear-surfaces than the fine-grained granites on which experimental velocity-values are available; or it may be that the aporhyolite seen lying in the exposed crystalline to the south extends up as a tongue beneath the Coastal Plain into this area and due to its physical appearance has been termed "granite" by the drillers. For the present this is as near a solution as can be offered to this problem since no physical data are known to be available on the aporhyolites except for their density which is 2.58.

In regard to the eastern portions of the Coastal Plain traverses no such marked correlation is again observed between the three sets of data.

There is, though, a relation between the magnetic and gravitational "low" in the Newport News - Norfolk area. The lack of agreement with the seismic velocities here may possibly be due to the second order of accuracy of these values as noted by Ewing [4].

Between this "low" and the preceding "high" a broad area occurs in which all three sets of data show gradual change. The seismic velocities and magnetic values are relatively higher than the norm and the gravity-values show little change. However, if the negative regional gravitational trend were removed, it is seen that agreement would be obtained among these three sets of data. From a consideration of the observations over the Piedmont, this area might well represent one underlain by the Wissahickon formation, and the low values observed in the Newport News area reflect an area of granites or granite gneisses.

Piedmont profile--As indicated in the introduction, the magnetic traverse was carried from Richmond to beyond Charlottesville in order to ascertain the magnetic behavior of the various crystalline formations which in all probability underly the Coastal Plain. From Figure 4 it will be noted that the Catoctin Greenstone series near Charlottesville are characterized by the greatest magnetic effect. These are ancient basaltic flows of high density (3.34) and apparently high magnetic susceptibility that have been altered to amphibolites. The Wissahickon mica schist, which is believed to represent altered sediments, is characterized by a somewhat smaller magnetic effect, and the granites and granite gneisses by the least magnetic effect. It will be noted that the hornblende gneisses have about the same magnetic effect as the granite gneisses although their specific gravity is essentially the same as the greenstones. So although the magnetic reflection would not differentiate the hornblende gneiss from the granites, the gravitational values should be different since the average density of the granites is 2.63. That this is the case is seen at Amelia where the gravity-station is located adjacent to a large hornblende dike and the anomaly is plus 21 milligals, and at Ettrick where the gravity-station lies on the granite and the anomaly is minus 19 milligals. The possibility of hornblendeite underlying the Prince George area of high magnetic, gravity, and seismic velocity-values therefore appears to be ruled out. The only other rock, observed in crossing the Piedmont, showing a marked magnetic characteristic was the small outcrop of metagabbro observed in the granite gneiss area not far from Richmond. A marked magnetic high was obtained here, and since this rock also possesses the high density and seismic velocity-values observed in the Prince George area, it would appear quite probable that this represents the actual rock present beneath this part of the Coastal Plain.

New Jersey Area: Cape May Traverse--Although no definite knowledge of the basement-rocks is available along this profile, the outcrops across the Delaware River at Chester show gabbro, Wissahickon schist, and granites in intimate relation with each other. It is therefore probable that these rocks in similar relations are present beneath the Coastal Plain across the river. From the magnetic profile (Fig. 5) it is seen that a series of "highs" occur separated by relatively narrow "lows." The gravitational and seismic velocity-values do not agree with each of these high anomaly-areas as observed in Virginia, but agreement is indicated for two of them, the second and fourth. Whether better agreement would be had with a closer spacing of gravity and seismic stations is problematical, and for the present no conclusions can be reached as to the nature of the basement except in a most general way; possibly a gabbroic type rock in these two areas of high magnetic values and not so high gravity and seismic velocity-values. For the rest of the profile the other magnetic highs may be associated with a variation of the Wissahickon schist and the lows with a granite or granite gneiss. There is little evidence offered by either the gravitational or seismic velocity data here either to support or discredit such assumptions.

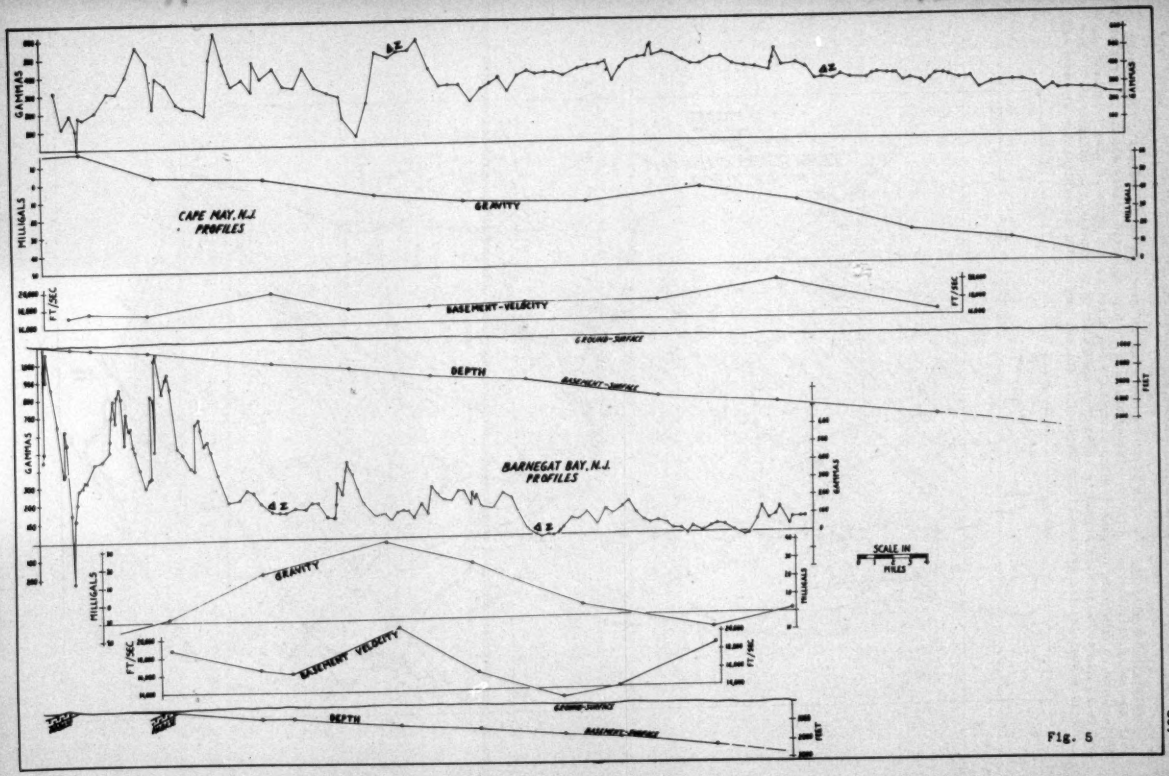
GAMMAS
MILLIGALS
FT/SEC.
CAPE MAY, N.J.
PROFILES
GRAVITY
BASEMENT-VELOCITY
GROUND-SURFACE
DEPTH
BASEMENT-SURFACE
FEET
BARNEGAT BAY, N.J.
PROFILES
SCALE IN
MILES

Fig. 5

Barnegat Bay Traverse--On this traverse (see Fig. 5) the first marked magnetic high occurs over the Rocky Hill diabase outcrop. The second area of high magnetic values occurs in a region believed to be underlain by gabbro, which outcrops a few miles to the south of this location. The third magnetically high region is known from well data to be underlain by diabase which is probably a step-faulted section of the Rocky Hill diabase sheet. For an explanation of the other

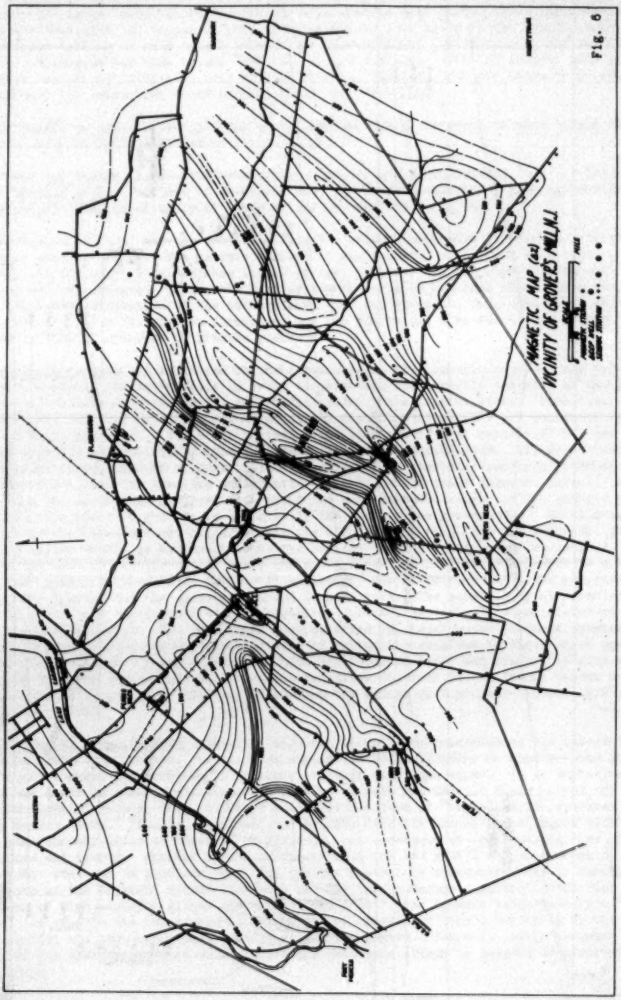

Fig. 6

magnetic highs there is no direct evidence and their control can only be surmised from other data. In Figure 6 the expanded areal survey of the westward end of the Barnegat Bay traverse is shown, and the areal extension of the second magnetic high, referred to above, can be seen, and also the linear form of the diabase beneath the Coastal Plain which is responsible for the third magnetic nigh. The fourth is the isolated "bump" which occurs just to the west of Hightstown. This occurs in an area known from well data to consist predominantly of gneisses and schists, and the interpretation of this feature may be that it is a reflection of subsurface basement-configuration rather than lithologic variations. For the fifth magnetic high on the Barnegat Bay profile, which occurs well out in the Coastal Plain, it appears that it is related to the gravitational and seismic velocity-nigh which occurs adjacent to it, in which case the control would appear to be lithologic and a gabbroic-type rock suggested. For the magnetic lows on this traverse, agreement is noted between the first and second with the seismic velocities, but the gravitational values appear to fit a more regional control. For the last rather broad magnetic low near the coast, agreement is had between the magnetic and the gravitational values but not the seismic velocity-values. The significance of the data in these areas is not understood and it is hoped that additional magnetic and gravitational work will clarify many of the present indications.

That such additional work is justified is indicated in Figure 6 where the possible extent of the buried diabase sill is indicated, the probable position of the gabbro from the south, and also near Plainsboro the strike of an east-west fault, seismically determined several years ago [2], but for which the strike and extent were not known.

Conclusions--On three traverses across the Coastal Plain of Virginia and two across the Coastal Plain of New Jersey it was found that definite correlations existed between seismic-velocity, magnetic, and gravitational observations. These three sets of data sometimes indicated "highs" and "lows" at the same locations and sometimes one set would be in opposition to the other two. Correlations of magnetic and gravity observations with the crystalline rocks of the Piedmont and their specific gravity values showed that definite relations might be expected for the various types of rocks. These data coupled with published information on the velocities of sound in different types of rocks indicate that with a more complete study it should be possible to map lithologic variations in the crystalline basement underlying the Coastal Plain sediments with a fair degree of accuracy as to the type of rock present.

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HEIGHT OF MAGNETIC ANOMALIES

H. Herbert Howe

One of the important duties of the United States Coast and Geodetic Survey in recent years has been the preparation of aeronautical charts. On these charts are shown isogonic lines, magnetic azimuths between important cities, or both. Questions have been raised regarding the extent to which magnetic anomalies observed at the surface would affect air navigation. In particular: (1) Should the irregularities shown by isogonic lines on a chart of the entire country be shown also on aeronautical charts? (2) Would anomalies observed at the surface of the Earth, but of too small extent to affect isogonic lines on the United States chart, be appreciable at the height of air navigation?

Plans have been considered to make actual flights over regions of known anomaly to determine the variation of the declination as accurately as would be possible in view of the difficulites of making observations under such circumstances, but as yet no such plan has been carried out. The present investigation was made to see what information about anomalies in the region of airplane-flight could be obtained theoretically from observations at the surface.

In this region, the magnetic field is derivable as the negative gradient of a potential V, since (a) there are no appreciable electric currents flowing, (b) there are no ferromagnetic materials, and (c) the permeability of the air is essentially constant. This potential satisfies Laplace's equation

$$\frac{\partial^2 V}{\partial x^2} \quad \frac{\partial^2 V}{\partial y^2} \quad \frac{\partial^2 V}{\partial z^2} = 0 \tag{1}$$

We follow the usual methods of deriving potential functions, using rectangular coordinates. Consider possible solutions of the form

$$V_0 = X(x) \quad Y(y) \quad Z(z) \tag{2}$$

where the functions X, Y, and Z are functions of, respectively, x, y, and z, and are to be determined. As usual, differentiate V_0, substitute into (1), and divide by V_0. We find that

$$X''/X + Y''/Y + Z''/Z = 0 \tag{3}$$

where X'' denotes d^2X/dx^2, etc. Since the three terms of (3) are, respectively, functions of x alone, y alone, and z alone, they cannot add to zero unless each one is a constant; for example, $X'' = (\text{Const.})X$, etc. Solving this, we see that X, Y, and Z must be exponential functions; that is, $X = (\text{Const.})e^{ax}$, where a is any complex constant. Hence (2) becomes

$$V_0 = C\, e^{ax}\, e^{by}\, e^{cz} = C\, e^{(ax+by+cz)} \tag{4}$$

where a, b, and c are complex constants. Substituting (4) into (1), it is found that the single condition on a, b, and c is

$$(a^2 + b^2 + c^2) = 0 \tag{5}$$

It may be shown that these functions V_0 form a complete set; that is, any potential may be expressed as the sum of such functions (or, if the potential be defined for an infinite range of x, y, and z, we must integrate with respect to continuously varying a, b, and c).

In addition to (5), further restrictions on a, b, and c are imposed by the boundary-conditions. For the purpose in question, it appears certain that we may assume the source of the magnetic field to lie entirely within the Earth; that is, we ignore the terms arising from external sources. Take the origin at the surface, z-axis upward. We know that V approaches 0 as we proceed indefinitely in the positive z-direction, in the positive or negative x-direction, or in the positive or negative y-direction. Hence in every term a and b must be pure imaginaries; for a factor e^{ax} with a real would approach infinity in one direction or the other, and the ΣV_0 would diverge for sufficiently large x. Then, to satisfy (5), c must be a real number; and to make the potential approach zero as we ascend from the Earth, c must be negative.

By the usual transformations between imaginary exponentials and trigonometric functions, we see that each elementary potential function must be of the form

$$\text{Const.}\ \sin(ax + \varphi)\ \sin(by + \theta)\ e^{-(\sqrt{a^2 + b^2})z} \tag{6}$$

where a and b are real numbers, and φ and θ are phase-angles.

For discussions of anomalies of limited extent, it will suffice to regard the surface of the Earth as the xy-plane. Then, in principle, we can from observations at the surface determine the potential at the surface, expand it in Fourier series to give the coefficients of (6) with $z = 0$, and then determine at once how rapidly each term diminishes with altitude. In practice, this cannot usually be done, but we can at least derive some useful information from this sort of argument.

For example, consider one term of the form (6). Let the mile be the unit of measure. Suppose the term in question has $a = 1$, $b = 0$. The factor $\sin(x + \varphi)$ goes from 0 to its maximum and back to 0 in a distance of 3.1 miles. The exponential term e^{-z} drops to one-third of its surface-value in 1.1 miles. In general, then, a potential varying in the x-direction as a sine-function and constant in the y-direction will drop to one-third at an elevation equal to one-third of the half-wave-length. By referring to (6), we see that if it varies in the y-direction also it drops off more rapidly with altitude.

Although any detailed analysis would require extensive observations and lengthy computation, we can in general infer that an anomaly becomes negligible at a height materially less than its linear dimensions at the surface. For example, it appears that regional anomalies shown on a small-scale isogonic chart are essentially unchanged within the height of airplane-flight, whereas local disturbances a few miles in extent would be practically negligible.

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DESCRIPTION OF MISSOURI SCHOOL OF MINES MAGNETIC OBSERVATORY

F. C. Farnham

(Abstract)

Last summer funds were appropriated by the Executive Committee of the Board of Curators for the erection and equipment of a small magnetic observatory at Rolla. The Observatory will consist of a set of three magnetic variometers which will give a continuous record of the variations in the horizontal intensity, the vertical intensity, and the declination of the Earth's magnetic field. These instruments will be housed in a variation-building which will be about 15 by 18 feet outside dimensions, well thermally insulated, and of completely non-magnetic construction. Also there will be an absolute building about eight by eight feet outside dimensions of non-magnetic construction and containing masonry piers on which instruments for measuring the absolute value of the strength and direction of the magnetic field may be set. The foundation- and pier-footings for the variation-building have been poured and the variometers have been purchased. It is planned to construct the absolute building immediately but funds are not now available for the absolute instruments.

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IONOSPHERIC MEASUREMENTS DURING THE SOLAR ECLIPSE OF APRIL 7, 1940

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Development of a quantitative theory for variations of ionization in the Earth's outer atmosphere requires a knowledge of the variation of ion-density in the ionosphere with radiation incident upon it. While diurnal and seasonal changes can be determined quite readily, these in themselves do not permit evaluation of several factors of the theory, such as effective recombination-coefficient and ion-production, with the desired precision. Rapid changes encountered during a solar eclipse provide material for much more critical examination of the theory [see 1 of "References" at end of paper] and more exact evaluation of the constants in the theory. This in turn provides information, otherwise difficult to obtain, about the physics of the Sun and about the ionosphere.

Observations of the ionosphere during the solar eclipse of April 7, 1940, were made at the Kensington Experimental Station, Department of Terrestrial Magnetism, Carnegie Institution of Washington (latitude 39° 01' north, longitude 77° 05' west) using automatic multifrequency apparatus of the type in service at the Watheroo and Huancayo magnetic observatories of the Department. Description of the apparatus and of the records may be found elsewhere [2]. During the control- and eclipse-observations the apparatus was speeded up to permit one complete set of measurements of all ionospheric layers each 5-5/8 minutes. Thus 26 complete records were made during the eclipse. In addition, control-data were obtained for several days before and after the eclipse to determine "normal" uneclipsed conditions.

We present here only the observed data because of the restrictions of available time on detailed theoretical computations. A more complete account of these computations will be presented at a later date together with a more general study of the E-region. The eclipse-data are referred to time of eclipse at the ground, though this is shifted toward sunset approximately two minutes for each 100 km of height above the Earth's surface at Kensington. In each Figure the data for the eclipse are compared with corresponding control-data for other days.

Data for maximum ion-density of the E-region are shown in Figure 1. In this Figure the observed quantity, namely, penetration-frequency, is plotted as ordinate; ion-density is pro-

portional to penetration-frequency squared. During the eclipse, values of penetration-frequency are well below control-data, returning to normal at the end of the eclipse. This is in general accord with the ultra-violet theory for ionization of this region. More detailed preliminary examination of the data has shown that values during the early part of the eclipse fall below calculated theoretical values using very high values of effective recombination-coefficient. This suggests that solar radiation responsible for E-region ionization does not emanate quite uniformly from all parts of the solar disc. Covering some of the more active areas of radiation during early stages of the eclipse could account for the rapid fall of ionization observed.

Measurements of F_1-region penetration-frequency are shown in Figure 2. The control-data are taken for two days before and two days after the eclipse. Merging of F_1- and F_2-regions made the F_1-region penetration-frequency unobservable after $17^h\ 30^m$ on April 7, 1940. Change of F_1-region ion-density follows the ultra-violet theory for production of the region in a general way. The rate of fall of ion-density for this region also is more rapid during the early stages of the eclipse than predicted by theory and by about the same amount as observed in the case of the E-region. This tends to support the view that the ultra-violet radiation producing the lower ionospheric regions may be radiated more intensely from some areas of the solar disc than from others.

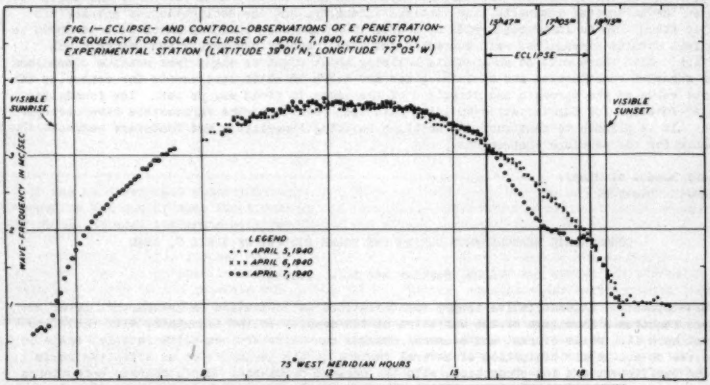
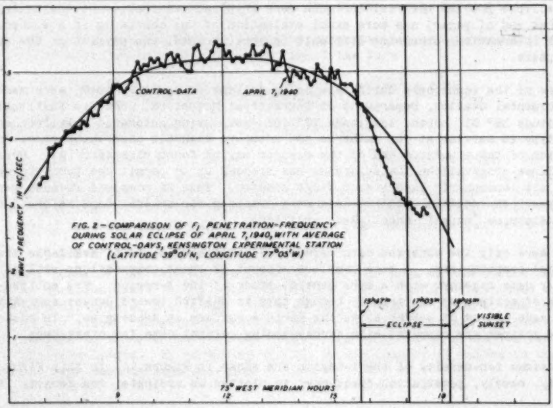


FIG. 1—ECLIPSE- AND CONTROL-OBSERVATIONS OF E PENETRATION-FREQUENCY FOR SOLAR ECLIPSE OF APRIL 7, 1940, KENSINGTON EXPERIMENTAL STATION (LATITUDE 38°01'N, LONGITUDE 77°05'W)
15h47m
17h03m
18h15m
ECLIPSE
VISIBLE SUNRISE
VISIBLE SUNSET
WAVE-FREQUENCY IN MC/SEC
LEGEND
× × × APRIL 5, 1940
× × × APRIL 6, 1940
○ ○ ○ APRIL 7, 1940
75° WEST MERIDIAN HOURS


CONTROL-DATA
APRIL 7, 1940
WAVE-FREQUENCY IN MC/SEC
FIG. 2—COMPARISON OF F_1 PENETRATION-FREQUENCY DURING SOLAR ECLIPSE OF APRIL 7, 1940, WITH AVERAGE OF CONTROL-DAYS, KENSINGTON EXPERIMENTAL STATION (LATITUDE 38°01'N, LONGITUDE 77°05'W)
15h47m
17h03m
18h15m
ECLIPSE
VISIBLE SUNSET
75° WEST MERIDIAN HOURS

The F_2-region presents somewhat different aspects. Data for the eclipse and for each of the control-days are plotted in Figure 3, while the eclipse-data are compared to the mean of the control-data in Figure 4. At the level of maximum ion-density of this region the eclipse occurs six to seven minutes after its incidence at the ground. Comparison of eclipse-data to the control-data alone leads to the almost certain view that the eclipse was responsible for the marked reduction of ion-density during this interval on April 7. It must be observed, however, that on April 9 and 10 (and to some extent on April 8) a somewhat similar fall of ion-density occurs during the eclipse-interval. Nevertheless, the fall of ion-density on April 7 appears to be more rapid than on any control-day during the eclipse-interval and it seems reasonable that to this extent, at least, the decrease in F_2-region ion-density can be attributed to decrease in incident ultra-violet radiation.

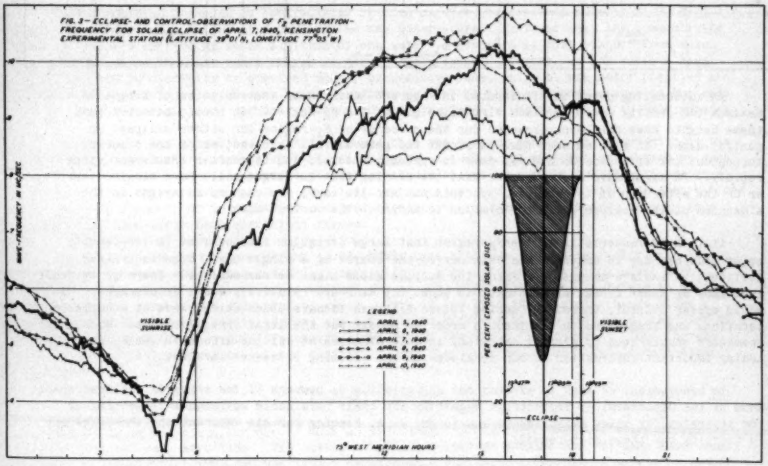


FIG. 3—ECLIPSE- AND CONTROL-OBSERVATIONS OF F2 PENETRATION-FREQUENCY FOR SOLAR ECLIPSE OF APRIL 7, 1940, KENSINGTON EXPERIMENTAL STATION (LATITUDE 39°01' N, LONGITUDE 77°03' W)
WAVE-FREQUENCY IN MC/SEC
PER CENT EXPOSED SOLAR DISC
VISIBLE SUNRISE
VISIBLE SUNSET
LEGEND
APRIL 5, 1940
APRIL 6, 1940
APRIL 7, 1940
APRIL 8, 1940
APRIL 9, 1940
APRIL 10, 1940
ECLIPSE
75° WEST MERIDIAN HOURS

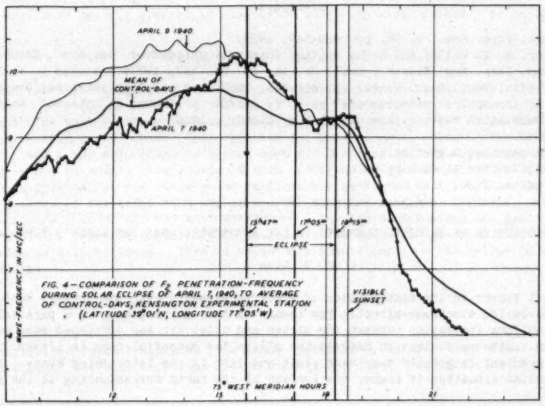


FIG. 4—COMPARISON OF F_2 PENETRATION-FREQUENCY DURING SOLAR ECLIPSE OF APRIL 7, 1940, TO AVERAGE OF CONTROL-DAYS, KENSINGTON EXPERIMENTAL STATION (LATITUDE 39°01' N, LONGITUDE 77°03' W)

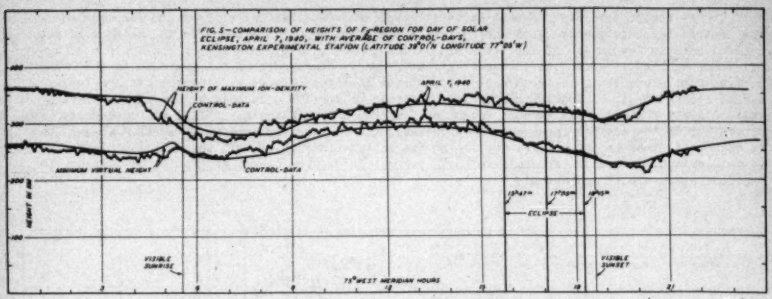


FIG. 5—COMPARISON OF HEIGHTS OF F_2-REGION FOR DAY OF SOLAR ECLIPSE, APRIL 7, 1940, WITH AVERAGE OF CONTROL-DAYS, KENSINGTON EXPERIMENTAL STATION (LATITUDE 38°01'N LONGITUDE 77°03'W)
HEIGHT OF MAXIMUM ION-DENSITY
CONTROL-DATA
APRIL 7, 1940
MINIMUM VIRTUAL HEIGHT
CONTROL-DATA
HEIGHT IN KM
ECLIPSE
VISIBLE SUNRISE
VISIBLE SUNSET
75° WEST MERIDIAN HOURS

An interesting point is illustrated in Figure 5 which shows the variation of height of maximum ion-density and of minimum virtual height of the F_2-region. It should be noted that these heights have not been corrected for the presence of F_1-region for either eclipse- or control-data. It will be seen that at sunset the general fall in height which has occurred throughout the afternoon on control-days is suddenly checked, and thereafter the height rises rapidly. It might have been expected that the evening rise in height would have occurred earlier on the afternoon of the eclipse, but this was not the case; the changes in height on the afternoon of the eclipse were very similar to those on the control-days.

It is a characteristic of the F_2-region that large irregular fluctuations in ion-density occur from one day to another, and even during the course of a single day. This fact makes it difficult to isolate changes for which the eclipse alone might be responsible. There is evidence that many of these irregular fluctuations about the mean are relatively local in character. It would appear helpful, therefore, during future eclipses to have observations made at a number of locations and these results combined in order to smooth out the local irregularities. Such a procedure should lead to greater certainty in determination of eclipse-effect in the F_2-region, adding important information to our knowledge of the ionizing processes involved.

In conclusion, we wish to express our appreciation to members of the staff of the Instrument-Shop of the Department of Terrestrial Magnetism for their invaluable assistance in setting up the apparatus for these measurements and to Dr. J. A. Fleming for his interest and encouragement in carrying out these measurements.

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THE DISTRIBUTION OF ELECTRIC ELEMENTS IN THE ATMOSPHERE NEAR THE EARTH'S SURFACE

O. H. Gish

An important factor in the distribution of electric elements near the Earth's surface is doubtless the so-called electrode-effect. The theory of this for the case of a parallel plate-condenser with uniform ionization between the plates and quiet air was developed some years ago by J. J. Thomson. With no ionization between the plates the potential-drop is linear. With ionization the gradient is greater near each plate and less in the intervening space. In the atmosphere a similar situation is found, the surface of the Earth corresponding to the negative

plate of the condenser. The gradient is greatest near the surface and decreases with altitude. In the air adjacent to the negative plate of the condenser, or in the air adjacent to the Earth, negative ions are repelled as fast as they are formed. In this space there are few negative ions, the positive ions being in preponderance. At the surface the current is conducted to the Earth wholly by the positive ions. The positive space-charge (ρ) represented by the excess of positive ions is related to the decrease of field-strength (E) with distance (x) from this plate by the relation $(dE/dx) = -4\pi\rho$. If the air is, as assumed, quiet and there is no mechanical transport of electricity in any way, the current-density, $i = \lambda E$, is independent of x. Here λ represents the electrical conductivity of the air. Then $(di/dx) = 0$ or $(\lambda dE/dx + E d\lambda/dx) = 0$, which by simple transformation gives $[id(1/\lambda)/dx] = -4\pi\rho$. The latter defines the manner in which the conductivity must depend upon the distance from the Earth for a given distribution of space-charge. Thus the reciprocal of conductivity, that is, the resistivity, must decrease with distance from the Earth or the conductivity must increase when the space-charge is positive.

This conclusion seems to be contradicted by some careful observations made by W. R. Hogg [see 1 of "References" at end of paper] at the Kew Observatory. He found that the conductivity from the Earth's surface up to an altitude of one meter is constant at that place. From this one would conclude that the space-charge is zero in this space. However, at the surface Hogg found that the conductivity is provided wholly by positive ions, while at one meter positive and negative ions contribute about equally. Therefore, one infers that the space-charge is not zero and we have here an apparent paradox. Attention will be given to the resolution of this paradox.

This paradox may be avoided if it is assumed that the current-density is dependent upon the distance from the Earth's surface or that $(di/dx) \neq 0$. Although the observations showed no such dependence, this is not an insuperable obstacle, because it has been found possible to assign a distribution of space-charge which, with all its consequences, is consistent with the observations to within the accuracy of measurement, provided electricity is transported toward or away from the Earth by some other than electrical forces.

If the electric conduction-current is dependent upon altitude, some electricity must be transported by means other than electrical conduction. Eddy-diffusion may bring about such transport. The current (flux of space-charge) due to eddy-diffusion may be expressed in a form similar to that for kinetic diffusion of gases. Thus if the gradient in space-charge along a normal to the Earth's surface is $(d\rho/dx)$ and A is the coefficient of eddy-diffusion, the flux of charge, taken positive when positive charge flows toward the Earth, is $A(d\rho/dx)$. This current plus the electrical conduction-current-density (i) may then constitute the total current-density (i_o), or

$$A(d\rho/dx) + i = i_o \qquad (1)$$

Now if i_o is the total current it must be independent of altitude when the space-charge density does not vary with time. The latter condition doubtless obtains for the data under consideration because they were derived from a considerable series of measurements made on a number of different days when general electrical conditions were relatively stable. It follows then that

$$d[A(d\rho/dx)]/dx + (di/dx) = 0 \qquad (2)$$

This shows that these two components if i_o vary in opposite sense with altitude.

For a case like that reported by Hogg, where the air-conductivity (λ) is independent of altitude, $(di/dx) = \lambda(dE/dx) = -4\pi\lambda\rho$. Then equation (2) becomes an equation in the variables ρ and x. The coefficient A has been found to depend upon x. One form of this dependence which has been used [2] is $A = (a + bx)$. A solution of this differential equation which satisfies the condition that ρ is greatest at the surface and continuously decreases as x increases is in terms of a Hankel function of the first kind and zero-order with the imaginary argument, $jk(a + bx)^{1/2}$; here j is the square root of -1, and $k = (4\pi\lambda/b^2)^{1/2}$. In this distribution the space-charge decreases very rapidly, near the surface, with increase of altitude but the rate of decrease steadily diminishes with altitude. This is shown more specifically by the following array of calculated values:

$(\rho/\rho_o) =$	1.00	0.50	0.30	0.25	0.20
when x =	0	5.5	51.0	92.0	170 cm

This distribution is distinguished from those indicated by earlier theoretical investigations [3] by its more rapid decrease very near the surface of the Earth. This initial rate of decrease

would be reduced if it is found that a larger value of the constant a is more appropriate for these particular circumstances.

Another aspect of this solution which is deemed important is that in the range x = 0 to x = 100 cm; this solution is very nearly the same as that which is obtained when the first term of equation (2) is set equal to zero. This implies (a) that both the conduction-current and the convection-current are practically independent of altitude in the first meter from the Earth's surface, (b) that the gradient is practically inversely proportional to the conductivity and hence independent of altitude. In fact, it is calculated that the gradient for conditions reported by Hogg should be only 1.5 per cent less at one meter than at the surface. This difference is too small to be readily detected by measurements made in the first meter or so from the Earth's surface.

One can not readily accept the indication of this solution that the convection-current is practically independent of altitude in the first meter because that seems to imply that positive space-charge is introduced into the atmosphere from the Earth, or negative charge transferred in the opposite direction, against the action of the Earth's electric field and at a rate greater than seems admissible. However, it seems unnecessary to face this difficulty because, assuming that the conductivity is dependent upon altitude by an amount too small to have been detected in those measurements, it is possible to express either ρ or E as a function of x of such form that when all variables satisfy equation (2) the results are approximately in agreement with the observations. A more extensive account of these investigations is in preparation.

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TOTAL AND UNCHARGED NUCLEI AT WASHINGTON, D. C.

K. L. Sherman

(Abstract)

Observations of the concentration of both uncharged and total condensation-nuclei were made at different times and places near Washington, using an Aitken nuclei-counter in conjunction with a cylindrical, electrical condenser through which air was drawn at a desired rate by a spring-driven turbine. The ratio (S) of the concentration of uncharged to that of all nuclei serves as a measure of the relative magnitude of the coefficients of combination and those of attachment between small ions and charged and uncharged nuclei, respectively, provided the assumptions usually made in this connection are valid. Diverse values of S have been found heretofore when these were determined from the same data but by different methods. It is shown in the theory of least squares that the method of determining the best estimate of a quantity of this character depends upon the manner in which weights should be assigned to the data. It is shown that the weight assigned to the observed number of particles falling on a square of the counter should vary inversely as that number. The proper method of determining the best estimate of S, when weights are assigned in this manner, and also two other simpler methods were applied to these data. The surprisingly small differences in the three results indicate these data are homogeneous.

From 620 individual samples of both uncharged and total nuclei, S was found to be 0.75 with a standard error of 0.02. This value of S is distinctly greater than that reported for other places but it is in close agreement with values previously determined at Washington with other equipment. No significant evidence of a dependence of S upon time, upon place, or upon concentration of nuclei, such as some observers report, is provided by these data. An examination of the standard deviation of S for a single sample indicates that the variations which do appear are no greater than those which are to be expected from random errors. Systematic errors in all measurements of this sort may arise from the adsorption of nuclei on the walls of the apparatus.

The differences in the values of S found at the different places may in part be attributable to this source. Four hundred individual samples taken both before and after the air passed through the condenser with no field applied indicate that 0.85 of the nuclei which enter this condenser get through. The procedure followed here was such that errors in the calculated value of S from this source are eliminated provided charged and uncharged nuclei are adsorbed with equal facility.

[The complete paper is published in the Journal of Terrestrial Magnetism and Atmospheric Electricity, v. 45, pp. 191-204, 1940.]

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THE NATURE OF SOLAR HYDROGEN VORTICES

R. S. Richardson

It is believed that spectroheliograms taken in the center of the $H\alpha$ line show us the solar atmosphere at the highest level observable. On such exposures the chromosphere has a fine granular structure resembling the skin of an orange. Near large spot-groups, however, it is drawn out into long filaments, indicating the presence of an extensive field of force. These filaments often remind us strongly of the arrangement of iron filings around a bar-magnet, or the lines of flow in a vortex.

This resemblance has naturally led to two explanations of the field of force around a spot-group. First, they are true magnetic fields produced by charged particles whirled around the spot at a low level. Second, they are hydrodynamical vortices whose form depends upon how the gases are flowing into or out of the spot.

The magnetic field of moderate intensity observed in sunspot umbrae distinctly favors the electromagnetic hypothesis. Störmer [see 1 of "References" at end of paper] has developed this idea on the assumption that the direction of curvature of the filaments (clockwise or counter-clockwise) depends upon the flow of an electric current far below the upper layers. In this way, he was able to account for many of the visible surface-features.

Störmer's theory can be put to a rather crucial test if we are allowed to assume that the charged particles in the low-level current always have the same sign in single spots, and in the preceding member of bi-polar groups. For then all spots with the same polarity must also have the same direction of whirl. Furthermore, when the reversal of polarity occurs at sunspot-minimum, there should also be a reversal in the direction of whirl in the two hemispheres.

Hale [2] applied this test to the best hydrogen whirls he could find on the spectroheliograms taken from 1908 to 1924. Since over 3,000 spot-groups were recorded during this time, and since hydrogen spectroheliograms are taken on every clear day at Mount Wilson, it might be supposed that hundreds of cases would be available for study. On the contrary, only 51 good examples were found. This circumstance was partly due to instrumental mishaps and the poor quality of plates then in use, but principally to the fact that well-marked whirls are exceedingly rare phenomena. Generally the filaments are so indefinite and so badly jumbled together, that not only is it difficult to determine the direction of whirl, but difficult to decide whether there is any whirl at all.

Hale was unable to discover a relationship between the polarities of the 51 selected whirls and their direction of rotation. That is, regardless of the spot's polarity, about as many whirled one way as another. But when grouped according to hemisphere, the direction of whirl for slightly more than 80 per cent of the spots agreed with that in terrestrial cyclones. Thus the observational evidence, although somewhat scanty, appeared to favor the hydrodynamic rather than the electromagnetic hypothesis.

These results are of the greatest importance in the interpretation of solar phenomena. It seemed advisable, therefore, not only to make use of the material that has accumulated since Hale's investigation, but also to reexamine the plates from 1908 to 1924. In this way, the data will be homogeneous over the entire interval, 1908 to 1939.

Two methods were tried. First, the one adopted by Hale of using a few highly selected

Table 1

Whirl	Cycle				Total
	1901-13	1913-23	1923-34	1934-45(?)	
	Northern Hemisphere				
Clockwise	0	27	25	30	25
Counter-clockwise	100	73	75	70	75
	Southern Hemisphere				
Clockwise	75	75	67	64	71
Counter-clockwise	25	25	33	36	29

Table 2

Whirl	Cycle				Total
	1901-13	1913-23	1923-34	1934-45(?)	
	Spots of positive polarity				
Clockwise	75	27	67	36	46
Counter-clockwise	25	73	33	64	54
	Spots of negative polarity				
Clockwise	0	75	25	38	55
Counter-clockwise	100	25	75	62	45

Table 3

Whirl	Northern Hemisphere		Southern Hemisphere	
	per cent	per cent	per cent	per cent
Clockwise	11.4	29	28.1	66
Counter-clockwise	28.0	71	14.7	34
Radial	30.0		25.1	
Indeterminate	30.6		32.1	

spots for which there could not be the slightest doubt as to the direction of whirl. The only difference was that while Hale used both single spots and the leading member of bi-polar groups, nothing but single spots was considered in the present investigation. Additional data were obtained by estimating the percentage of filaments around all good single spots that were clockwise, counter-clockwise, radial, and indeterminate. This procedure was carried out quite apart from the first investigation with the highly selected spots. While these spots were necessarily included in the second list, the estimates were made independently of them. Although they can not be given the same weight as those in the first list, it was felt that they should at least constitute supporting evidence.

The observations extending over the 32 years from 1908 to 1939 include examples from four sunspot-cycles, with three reversals of polarity at the minima of 1913, 1923, and 1934. There were 141 whirls in the first class list, and 225 for which the direction of rotation was more or less indeterminate.

The results for the former are given in Tables 1 and 2. Table 1 shows these data arranged according to hemisphere. It is seen that throughout all four cycles the direction of rotation is predominantly the same as in terrestrial cyclones. The percentage is somewhat smaller than that found by Hale, probably owing to the larger number of cases.

Table 2 contains the same data as Table 1 arranged according to magnetic polarity. When presented in this way, the majority of vortices surrounding the spots appear to reverse their direction of whirl from one cycle to the next. Now the basic assumption of the electromagnetic hypothesis is that the direction in which the charged particles are whirled determines the polarity of the spot. Hence, if the direction of whirl changes but the polarity remains the same, then we are forced to conclude that the sign of the charged particles must also have changed. Although such a possibility cannot be ruled out entirely, it seems so unlikely that we much prefer quite a different conclusion, namely, that there is no connection whatever between the direction of whirl and the polarity of the spot.

Table 3 contains the results for the miscellaneous material. Despite the fact that these

include the 141 first-class examples, with a weight of nearly 100 per cent clockwise or counter-clockwise, the majority are either radial or indeterminate. However, the relative percentage of filaments estimated as clockwise or counter-clockwise in either hemisphere agrees closely with the values in Table 1.

This persistent agreement between the direction of whirl in hydrogen vortices with that in terrestrial cyclones is strongly in favor of the hydrodynamical hypothesis. Apparently the direction the vortex shall take is determined largely by the solar rotation, just as the Earth's rotation tends to establish a circulation of air to the right or left in cyclones of the Northern or Southern hemispheres. On the Sun, exceptions might easily arise from the slow change in the velocity of rotation with latitude, or violent turbulence in the formation of active spots.

A point which so far has received no attention is the percentage of whirls having different degrees of curvature. Well-marked hydrogen whirls resemble logarithmic spirals so closely that they may be conveniently described by curves of this form. The shape of the spiral is then determined by angle, ω. For small values of ω, the lines of force are nearly radial, while closely wound spirals correspond to values ranging from 60° to 90°. Using the 141 first-class cases, this angle was estimated in steps of 10° by comparing the photographs with the diagrams in Störmer's paper. The results show that small values of ω predominate, 62 per cent being open spirals with values of ω of 20° or less. Closely wound spirals are very rare, although they do occur.

Another consequence of Störmer's theory is that the strength of the magnetic field along the line of sight is proportional to cos ω. This component can be measured from the broadening of the spectral lines produced by the Zeeman effect. No evidence could be found, however, to indicate the existence of a relation between the form of the spiral and the field-strength at its center.

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THE EVALUATION OF MAGNETIC ANOMALIES BY MEANS OF SCALES

Irwin Roman
(Published with the approval of the Director, U. S. Geological Survey)

(Abstract)

At the 1939 meeting of the Union [Fundamental research in geophysics relating to prospecting, Trans. Amer. Geophys. Union, 1939, pp. 302 and 390], the writer described a set of scales for aiding in the evaluation of the magnetic anomaly due to a selected magnetized body. During the past year, these scales have been modified in several minor details. The revised forms are shown by typical scales illustrated in Figure 1.

The present discussion illustrates the use of these scales for a possible geologic body and reports the agreement between the measured and theoretical results in certain examples for which the latter have been calculated.

For the graphical evaluation, the map is drawn to the same scale as that used in constructing the scales. A rectangular grid is superposed on this map and the work-sheet thus obtained is fastened to a drawing-board. A pin is inserted at the point of the map corresponding to the station-point at which the anomaly is to be evaluated. Each grid-point is measured with the scale corresponding to the proper depth-value. The scale-readings for points on the top or south side of the body are considered as positive, those on the bottom or north side as negative. Each reading is adjusted for the area controlled by the point and the algebraic sum of these products is modified for the magnetic inclination to furnish the anomaly.

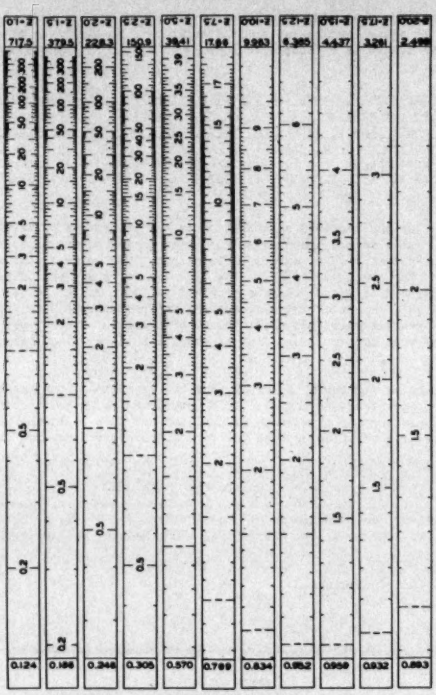

Fig. 1--Typical scales

Table 1--Agreement of graphical with theoretical values of magnetic anomalies

Body	Station	Field	Theoretical value	Graphical value	Discrepancy (per cent)
Horizontal rectangle S5 - N5, W6 - E6, z = 4	Origin	Vertical	2828.9	2807.5	0.8
Horizontal circle Radius $\sqrt{6}$, center (0,0, 4.5)	Origin	Vertical	963.5	951.6	1.2
Top surface of spherical lamina Radius 18, center (0,0,32) Depth from 14 to 18	Origin	Vertical	1219.2	1215.1	0.3
Complete sphere Radius 4.5, center (0,0,8)	W5, S$\sqrt{11}$, 0	Vertical Horizontal	351.2 303.8	347.8 306.2	0.3 0.8

Table 2--Reproducibility of readings

Reading-discrepancy	Number of cases with second reading		Total number readings
Units	Larger	Smaller	
0	none	none	402
0.1	185	217	402
0.2	50	28	78
0.3	7	5	12
0.4	10	3	13
0.5	none	4	4
0.6	none	3	3
0.7	3	none	3
0.8	none	none	none
0.9	2	2	4
1.0	1	1	2
>1.0	1	1	2
Total	259	264	925

For a few bodies, the anomaly is available by integration. Table 1 shows the agreement between the measured and computed values for several such examples.

To test the reliability of the readings made with the scales, the same map was read for the same grid and station-point a second time. Three weeks elapsed between the two sets of readings. Different black-line prints of the same tracing were used. The scales were on bristol-board strips and had been in use for over a year, so that there was some slight play about the pivot. Table 2 shows the agreement between the two sets of readings arranged according to the discrepancies. The average reading was about 50 and the discrepancy in the final value of about 1,100 units was six units. The larger discrepancies occurred at points near which a change of one unit in the scale-reading corresponded to an actual distance of one-fortieth of an inch along the edge of the scale-strip.

To study the effect of changing the map unit without changing any other factors, the top segment of a sphere was represented on three drawings, the unit-length of the body being represented by 1, 2, and 4 inches, respectively. For each drawing, the contour-interval was that which corresponded to one half-inch in the map, and the grid was composed of half-inch squares. For each drawing, the anomaly measured for the point of the drawing directly over the center of the sphere was less than the computed value, but the relative error decreased as the drawing-size and the consequent number of grid-points increased. The details are shown in Table 3.

Table 3--Effect of contour-map size

[Anomaly for top surface of a segment in a sphere whose center is directly below the station-point]

Size-factor	1	2	4
Radius of sphere, inches	4.5	9	18
Depth of center of sphere, inches	8	16	32
Depth to top of segment, inches	3.5	7	14
Depth to bottom of segment, inches	4.5	9	18
Number of contour-curves	3	5	9
Number of grid-points	145	481	1789
Theoretical value	1219.2	1219.2	1219.2
Measured value	1168.0	1198.3	1215.1
Deficiency of measured value	51.2	20.9	4.1
Relative deficiency, per cent	4.2	1.7	0.3

With proper modifications in the method of analysis, the scales are also available for other problems, including gravitational attraction, distribution of light-intensity, and electric field-intensity.

U. S. Geological Survey,
Washington, D. C.

PROGRESS-REPORTS

RESEARCHES IN TERRESTRIAL MAGNETISM AND ELECTRICITY AT DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON, FOR YEAR APRIL 1939 TO MARCH 1940

J. A. Fleming

The work of the Department in the fields of terrestrial magnetism and electricity during the year has been characterized by the continued reduction and intensive study of observational data obtained in the field and at the observatories. An outstanding event, in which the Department had a large part, was the Seventh General Triennial Assembly of the International Union of Geodesy and Geophysics at Washington, D. C., September 4-15, 1939. This year has also been marked by the publication (August 1939) of "Terrestrial magnetism and electricity," which is volume VIII of the "Physics of the Earth" series sponsored by the National Research Council. Of the 14 authors contributing to this volume, eight are members of the Department's regular staff.

Magnetic investigations--The anomalies in magnetic vertical intensity measured last year by the Department in cooperation with the Geophysical Laboratory in the vicinity of the Santa Maria Volcano in Guatemala were reduced and plotted. These data were insufficient in number to afford a satisfactory geological interpretation and are being supplemented by additional observations made during February and March 1940. A topographical map of the immediate vicinity of the volcano was constructed on the basis of notes and measurements taken during the magnetic survey.

The study of the declination in geological ages was continued. A more extensive collection of varves from the Hartford series was collected and prepared for measurement.

Records of the great magnetic storms of January and April 1938 were obtained and investigated. World-wide changes during the storm of April 16, 1938, revealed several remarkable features. Although the range of the storm was very great, it appeared to run through its phases with an unusual rapidity--the transition from the initial "positive" phase to the main "negative" phase was accomplished within two hours after the beginning of the storm.

A physical representation of the Earth's magnetic field by an appropriate distribution of dipoles within the Earth was accomplished, using the vertical-intensity values for 1922. The general magnetic field of the Earth may be represented to within the reliability of the observations by a dipole near the center (moment 8×10^{25} cgs units), giving rise to about 80 per cent of the field, and 14 secondary radially directed dipoles (average moment 0.1×10^{25} cgs units) located at specified positions midway between the surface of the Earth and its center, giving rise to the remainder or residual field. Secular change can be represented by the yearly addition of 13 dipoles of equal strength (moment 1.4×10^{22} cgs units) at the same depth as the dipoles of the residual field. Continuance of secular change at the present rate for 100 years would thus build up a new residual field. Interpretation of this representation indicates (1) at least a considerable portion of the Earth's magnetism (the residual field) originates at a lesser depth than the central core revealed by seismological evidence and (2) secular change involves this residual field and therefore is due to changes taking place between the surface of the Earth and the surface of the central core. Maps of the residual fields for epochs 1885, 1922, and 1939.5 show the gradual migration of this field.

A new measure of magnetic activity, the three-hour-range index K, was proposed and accepted by the International Union of Geodesy and Geophysics at the Washington Assembly in September 1939. An immediate detailed study of this measure, based on observatory-data of the Carnegie Institution of Washington and the United States Coast and Geodetic Survey, was published in December 1939 [see 2 of Publications at end of paper]. The main features of solar daily variations were also investigated and reported for the same material [3].

The Moon's influence on the horizontal intensity at Huancayo was further studied and large geomagnetic tides were found.

Solar influences on the Earth's magnetism are of two kinds, provisionally designated as W (wave-radiation) and P (particles). Both vary with the sunspot-cycle, but with significant differences. The range-index K is a satisfactory measure for P; studies on a similar day-to-day measure for W, derived from ranges of magnetic solar daily variations, were begun. The correlation-coefficients between a tentative magnetic measure for W (based on Huancayo records of 1922-39 alone) and relative sunspot-numbers were found to be as high as 0.984 in annual means.

Estimates were made of the current-distribution and intensity of electric current-systems in the atmosphere reproducing the disturbance-field of moderate magnetic storms of the Polar Year 1932-33. Results from individual hours of the main phase of storms show good agreement with findings of Chapman for the averaged main phase of many storms. The initial phases of two storms reveal current-systems weaker than those for the main phase and of radically different type.

Studies of magnetic storms suggest that the atmospheric current-system responsible for the daily variation of disturbance arises in part from electromotive forces generated mainly along the auroral zone.

A general theory of analysis of surface magnetic fields was developed. This new method permits the analysis of fields (such as those of magnetic storms) to which it is impracticable to apply the method of spherical harmonic analysis.

Geoelectric investigations--During the intense magnetic storms of January 1938, it was found that violent ionospheric effects occur on such occasions at the geomagnetic equator. Records from the Huancayo Magnetic Observatory show clearly a marked expansion or "blowing up" of the F_2-region and increased wave-absorption during the disturbances [6]. Thus modern recording methods are greatly extending the knowledge of effects associated with magnetic disturbance.

Further studies of the correlation of conditions of radio transmission and magnetic activity were made. For the first four months of 1938 a correlation-coefficient of 0.74 was obtained between daily values of the American magnetic character-figure C_A and the transmission-disturbance figure of the Bell Telephone Laboratories, a number proportional to the depression of the signal-strength below normal in decibels. A correlation-coefficient of 0.70 was obtained between the magnetic index-range K and the transmission-disturbance figure for the same period. The correlation-coefficient relating C_A to K for the same period was 0.94--a remarkably close agreement for the two independent measures of magnetic activity.

A high correlation between the activity of electric currents in the Earth and solar activity, as measured by sunspot-numbers, was more completely verified, and this correlation was shown to hold for month-to-month variations.

New tests to determine the polarization of radio waves returned vertically from the ionosphere at the magnetic equator over a wide range of frequency (3.2 to 16.0 mc/sec) using modern multifrequency recording methods were conducted at the Huancayo Magnetic Observatory. These show that the polarization was essentially plane with the ordinary wave polarized in the north-south magnetic plane and the extraordinary wave at right-angles to it, with practically negligible minor axes of polarization, agreeing with earlier and more restricted experiments. Thus both branches of the multifrequency record were recorded quite separately under the appropriate conditions.

General dissemination of data is necessary to make possible study of variations of the ionosphere over the Earth's surface. Current ionospheric results from the Huancayo and Watheroo magnetic observatories are now published in the scientific literature in the form of quarterly reports.

Determination of the real distribution of ion-density with respect to height in the outer atmosphere has heretofore constituted a complicated problem in ionospheric research. It has been shown that translation of the virtual height of the ionosphere into actual height can be achieved by fitting a parabolic maximum of electron-density to observations of variation of virtual height with wave-frequency. The simplest measure of the actual height of maximum electron-density is the virtual height at five-sixths of the penetrating frequency [8]. This measure is found to be remarkably reliable for F-region at night. During the daytime it is often necessary to correct F_1-observations for presence of the E-region and F_2-observations for presence of F_1-region. The disadvantages of minimum virtual height for quantitative study of diurnal variation of ionospheric height are emphasized.

The recombination-coefficient of ions from a flame of illuminating gas was determined by Kennedy who found a value of 0.64×10^{-9}. Hogg estimated a value about 27 times this for large (Langevin) ions of the atmosphere. In view of the considerable difference in these values, the coefficient of the ions from a gas flame was redetermined. Ions from a flame were allowed to accumulate to high concentrations in a closed room after which the rate of diminution was measured; the value for the coefficient found was 15×10^{-9}--in good agreement with Hogg's estimate. The average number of unit-charges per ion reported by Kennedy was 4.6, but in this investigation it was found to be unity. For equilibrium-conditions, the rates of uncharged to

charged particles of one sign originating in the burning gas was about five. The number of negative ions exceeded the number of positive by about 15 per cent.

In explaining the increased ionization below the E-region during a chromospheric eruption, it is important to know definitely whether molecular ions (as well as large ions) are formed by ultra-violet light. Tests designed and made at the Department show definitely that they are formed in air by radiations from a mercury lamp. These ions (average age about 0.2 second) were found to have a mass double that of molecular ions formed by radioactive matter in air.

Good progress was made on the preparation of the atmospheric-electric data obtained since 1924 at the Watheroo and Huancayo observatories.

In connection with the volcanic studies in Guatemala reported last year, an electric resistivity-survey was made during December 1939 to February 1940 to determine the structure of the volcanic plains near Santa María Volcano and near Guatemala City. The results of this work are now being studied.

There was designed and constructed at the Department a portable apparatus for use on the proposed National Geographic Society - University of Virginia Expedition in the Pacific Ocean--postponed, after all arrangements had been effected, on account of the war--to determine the ratio of the total concentration of Aitken nuclei to that of the uncharged nuclei. This apparatus was subsequently employed for measuring this ratio in the vicinity of Washington. The ratio found was greater than that reported from a number of foreign stations.

There was also designed and constructed a portable apparatus for obtaining a measure of the rate of ionization in the atmosphere. The immediate use made of this apparatus was to ascertain whether unusual radioactivity exists in the neighborhood of volcanoes.

Observatory-work--The Department's observatories at Huancayo, Peru, and Watheroo, Western Australia, continued their extensive geophysical programs including continuous records of geomagnetic, geoelectric, and meteorological elements.

Cooperative work was continued with the following observatories: Atmospheric-electric program at Apia, Western Samoa; atmospheric-electric and earth-current programs at Tucson, Arizona; maintenance of international magnetic standards at the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey; and, through loan of apparatus, with the Cape Town Magnetic Observatory (South Africa) and the Royal Alfred Observatory (Mauritius).

Publications--The activities of the Department are set forth in greater detail in Year Book 38 of the Carnegie Institution of Washington. A few of the papers published during the last year are listed below.

[1] J. Bartels, Das Nordlicht vom 24.-25. Februar 1939 in Deutschland und die erdmagnetischen Störungen in Niemegk, Beitr. Geophysik, v. 55, pp. 195-203, 1939.
[2] J. Bartels, N. H. Heck, and H. F. Johnston, The three-hour-range index measuring geomagnetic activity, Terr. Mag., v. 44, pp. 411-454, 1939.
[3] J. Bartels and H. F. Johnston, Main features of daily magnetic variations at Sitka, Cheltenham, Tucson, San Juan, Honolulu, Huancayo, and Watheroo, Terr. Mag., v. 44, pp. 455-469, 1939.
[4] J. Bartels, Some problems of terrestrial magnetism and electricity, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 385-433, 1939.
[5] L. V. Berkner, The nature of radio fade-outs and their relation to bright chromospheric eruptions, Cinquième Rapport, Comm. Relations Solaires et Terrestres, pp. 76-84, 1939.
[6] L. V. Berkner, H. W. Wells, and S. L. Seaton, Ionospheric effects associated with magnetic disturbances, Terr. Mag., v. 44, pp. 283-311, 1939.
[7] L. V. Berkner, Radio exploration of the Earth's upper atmosphere, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 434-491, 1939.
[8] H. G. Booker and S. L. Seaton, Relation between actual and virtual ionospheric height, Phys. Rev., v. 57, pp. 87-94, 1940.
[9] S. Chapman, solar influence on the Earth's magnetism and on the upper atmosphere, Cinquième Rapport, Comm. Relations Solaires et Terrestres, pp. 111-115, 1939.
[10] S. Chapman, The lunar tide in the atmosphere, Met. Mag., v. 74, pp. 274-281, 1939.
[11] C. R. Duvall, Magnetic declination in the Pacific from observations by the Galilee and Carnegie, Terr. Mag., v. 44, pp. 115-136, 1939.
[12] J. A. Fleming, The Earth's magnetism and magnetic surveys, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 1-58, 1939.

[13] J. A. Fleming (Editor), Terrestrial magnetism and electricity, v. VIII of Physics of the Earth monographs prepared by the National Research Council, ix + 794 pp., 1939 [New York, McGraw-Hill Book Co., Inc.].
[14] J. A. Fleming, H. D. Harradon, and J. W. Joyce, Seventh General Assembly of the Association of Terrestrial Magnetism and Electricity at Washington, D. C., September 4-15, 1939, Terr. Mag., v. 44, pp. 471-479, 1939.
[15] J. A. Fleming and O. H. Gish, Annual report of the Director of the Department of Terrestrial Magnetism, Carnegie Inst. Wash., Year Book No. 38, pp. 57-105, 1939.
[16] S. E. Forbush, World-wide changes in cosmic-ray intensity. Rev. Modern Phys., v. 11, pp. 168-172, 1939.
[17] O. H. Gish, Atmospheric electricity, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 149-230, 1939.
[18] H. D. Harradon, Bibliographical notes and selected references, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 679-778, 1939.
[19] E. A. Johnson, W. H. Mock, and R. E. Hopkins, The limiting sensitivity of the alternating-current method of photo-cell-current amplification. J. Optical Soc. Amer., v. 29, pp. 506-511, 1939.
[20] E. A. Johnson, R. C. Meyer, R. E. Hopkins, and W. H. Mock, The measurement of light scattered by the upper atmosphere from a searchlight beam. J. Optical Soc. Amer., v. 29, pp. 512-517, 1939.
[21] T. H. Johnson, The angular dispersion of the cosmic radiation in the upper atmosphere resulting from deflections of low-energy particles in the Earth's magnetic field. Phys. Rev., v. 56, pp. 226-231, 1939.
[22] T. H. Johnson and J. G. Barry, The east-west symmetry of the cosmic radiation at very high elevations near the equator and evidence that protons constitute the primary particles of the hard component. Phys. Rev., v. 56, pp. 219-226, 1939.
[23] H. F. Johnston, J. A. Fleming, and H. E. McComb, Magnetic instruments, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 59-109, 1939.
[24] A. G. McNish, On causes of the Earth's magnetism and its changes, physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 308-384, 1939.
[25] W. J. Rooney, Earth-currents, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 270-307, 1939.
[26] O. W. Torreson, Instruments used in observations of atmospheric electricity, Physics of the Earth--VIII, Terrestrial magnetism and electricity, pp. 231-269, 1939.

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MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1939 TO MARCH 1940

N. H. Heck

During the past 12 months the United States Coast and Geodetic Survey has actively pursued a comprehensive program of magnetic work. In addition to established cooperative problems and the usual routine details, particular attention has been given to: (a) The problems of bringing up to date the repeat-survey of the United States, particularly the declination; (b) a repeat-survey of Alaska; (c) major construction projects at two observatories; (d) the improvement of field- and observatory-instruments and technique; (e) the preparation for ultimate publication of data obtained from accumulated observatory-records.

Magnetic surveys--In an effort to bring up to date the repeat-observations for magnetic declination for the United States, to be used in the preparation of the isogonic chart of 1940, one full-time magnetic observer was kept in the field for several months last year, and starting early in April, 1940, it is planned to send out two observers so as to complete the work during 1940.

Professor E. H. Bramhall of the University of Alaska was employed as a magnetic observer of the Bureau during the summer of 1939, and in the course of about two months he made complete repeat-observations at 27 stations in Alaska, using automobile, railroad, boat, and airplane transportation. Of a total of 4,800 miles traveled, 3,000 were by plane. It is of interest to note that intervals between stations that had taken a week or more to cover by boat in 1928 were readily spanned in a few hours by air. Two or three stations in the far north still remain to be occupied before data will be sufficient for the preparation of the next edition of the Alaska Tables and Charts. These are to be observed this spring.

During a part of the year, in addition to regular magnetic field-parties, magnetic observers attached to five triangulation-parties made observations for declination at or near triangulation-stations. Regular Bureau personnel attached to other field-parties continued to observe declination as in the past. Compass-declinometers and the new transit-magnetometer were used for this work.

Declination-observations were made at 74 stations in Alaska and 751 stations distributed over the following States: Alabama; California; Colorado; Idaho, Illinois; Indiana; Kansas; Kentucky; Louisiana; Maine; Maryland; Michigan; Mississippi; Missouri; Montana; Nevada; New Hampshire; New York; Ohio; Oklahoma; Oregon; Pennsylvania; Texas; Vermont; Washington; and Wisconsin. Repeat-observations for declination only were made at 36 stations distributed over the following States: California; Illinois; Indiana; Iowa; Kansas; Michigan; Minnesota; Nebraska; New York; North Dakota; Ohio; Oregon; Pennsylvania; South Dakota; Texas; West Virginia; and Wisconsin. Repeat-observations for horizontal intensity, in addition to declination, were made at one station in Illinois, one in Michigan, and one in New York. Complete repeat-observations were made at 27 stations in Alaska. Miscellaneous observations included several ship-swings, and whale-boat observations with a standard compass at two points in the Gulf of Mexico.

Magnetic observatories--The five magnetic observatories maintained by the Bureau operated continuously throughout the year.

At Tucson, a new variation-building was constructed to replace the original structure built in 1909. The latter had been damaged to such an extent by dry-rot and termites that it was not practicable to consider repairs or reconditioning. The new building is of concrete and frame construction, non-magnetic, and is placed partially underground for thermal-insulation purposes. For additional insulation, thick layers of sawdust have been provided around and above the variometer-room. It is planned to have this building in operation by the end of 1940, and at that time the old variation-observatory will probably be razed.

As a result of Naval operations, building construction at Sitka has been tremendously accelerated during the past two years. Because of this, it was recognized over a year ago that the present observatory-site would soon be rendered unsuitable for magnetic operations. As a result, a large plot of land about a mile from town was obtained by transfer from the Forest Service, and the construction of the necessary buildings for a magnetic observatory is now under way. Magnetic absolute observations were started in the new absolute observatory in January, 1940. A temporary variation-observatory has been completed and the magnetograph was moved to this structure the middle of April. In May, 1939, absolute values were transferred from the old absolute observatory to a pier located near the site of the new absolute building. Early in 1940, a final transfer was made from this pier to the new absolute pier, and these observations are now being reviewed in the Washington Office of the Bureau.

In March, 1940, plans were formulated for insulating and providing temperature-control for the east absolute wing at Cheltenham. When completed, these improvements will permit the maintenance of absolute instruments at relatively constant temperatures, in addition to providing a means for making controlled temperature-coefficient tests of various instruments. The work was initiated primarily because of the new electromagnetic standard being constructed by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, which when completed will be operated at Cheltenham.

A sealed cover with a breather tube containing a dehydrating chemical for the San Juan variometers is being designed in Washington, the purpose of which is to protect the instruments from the excessive relative humidity which exists at the Observatory. It will be somewhat similar to covers already used successfully in connection with the Wenner seismometers at San Juan.

The la Cour Z-variometer installed at Honolulu last year has continued to operate in a very satisfactory manner.

Cooperative work--Through cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the following projects have been carried on:

(a) Use of the sine-galvanometer and standard earth-inductor of the Carnegie Institution of Washington at Cheltenham was continued.

(b) At Cheltenham, the cosmic-ray meter of the Committee on Coordination of Cosmic-Ray Investigations of the Carnegie Institution of Washington was kept in continuous operation throughout the year. Space is being provided for the installation of a second meter in the near future.

(c) Standardization of field-instruments of the Carnegie Institution of Washington was done by personnel of that organization at Cheltenham.

(d) The perminvar Z-variometer of the Carnegie Institution of Washington was operated on an experimental basis at Cheltenham until early in April, when it was dismantled preparatory to moving it to the Department of Terrestrial Magnetism where it is to be set up and operated as an insensitive instrument for the present. Over four years of continuous records were obtained with this instrument at Cheltenham.

(e) Continuation of the atmospheric-electric and earth-current programs at the Tucson Magnetic Observatory. The Mountain States Telephone and Telegraph Company and the American Telephone and Telegraph Company also cooperated in the latter of these two programs.

(f) Contribution to broadcast and publication of daily magnetic data was continued. (In this connection, see "Special projects and investigations.")

Special projects and investigations--Bureau personnel took a very active part in the Seventh Assembly of the International Union of Geodesy and Geophysics, held in Washington in September 1939.

At this Assembly, it was proposed in a meeting of the Association of Terrestrial Magnetism and Electricity that a new measure of magnetic activity, known as the "three-hour-range index" be given a trial at various magnetic observatories throughout the world, this trial to last for a period of three years, from 1940 to 1942. The United States Coast and Geodetic Survey immediately began a cooperative study with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington of observatory-records from Cheltenham, Honolulu, San Juan, Sitka, Tucson, Huancayo, and Watheroo. By making comparisons with Niemegk for which indices have already been assigned, suitable scales were selected and records starting the first of January, 1938, were investigated. At the present time, three-hour-range indices, or K-numbers, have been assigned for Cheltenham and San Juan from January 1, 1938, to date. Sitka is complete for the two years 1938-39, and Honolulu and Tucson have been done for the first half of 1938. Cheltenham began the daily assignment of K-numbers on February 1, 1940, and the other four Coast Survey observatories took up the work on April 1, 1940. The Cheltenham figures are sent each day to Science Service with the daily Ursigram message, and the information is disseminated by broadcasting from Naval radio stations NAA and NPG and by the distribution of weekly summaries by Science Service.

A field vertical-intensity variometer of the type in common use in geophysical prospecting was used with success to determine absolute values of vertical intensity at stations near the Cheltenham Observatory, and also to establish station-differences of vertical intensity between observatory-piers at Cheltenham.

Work on the portable magnetic observatory was continued. Special attention was given to the tent and its supporting frame.

The Bureau took an active part in the training of personnel and the preparation of instruments for the program of terrestrial-magnetic and auroral observations to be made by the United States Antarctic Expedition. The Department of Terrestrial Magnetism of the Carnegie Institution of Washington cooperated in supplying certain magnetic instruments. Two of the Expedition's observers were trained at Cheltenham, and all magnetic absolute instruments were standardized at that Observatory. In addition, the magnetograph was set up and tested prior to its shipment to the Antarctic Continent.

Work on records--Work on observatory records, with particular emphasis on those for the Polar-Year period 1932-33, has progressed in a fairly satisfactory manner. Tabulations of the final results for the Cheltenham Observatory for this period have been printed, although necessary explanatory material is not yet ready. The Works Progress Administration Computing Office in New York, with D. G. Knapp in immediate charge of magnetic work, has made excellent progress on computations for the Polar-Year observatory, which was located at College, Alaska. In addition, a Works Progress Administration project has been in operation at the San Juan Observatory, where observatory-records for the Polar-Year period have been rescaled.

Publications--Members of the Bureau have given lectures and presented papers before various educational and scientific organizations. Some of the various papers are listed below:

H. E. McComb and J. W. Joyce, The application of new instruments to magnetic field work, Trans. Amer. Geophys. Union, 1937, pp. 364-366.

H. H. Howe, The Earth's quadrupole moments, Trans. Amer. Geophys. Union, 1939, pp. 359-364.
N. H. Heck and J. W. Joyce, The magnetic survey of the United States Coast and Geodetic Survey as applied to the structure of the Pacific Area, Sixth Pacific Science Congress, Berkeley, California, August, 1939.
H. E. McComb and J. W. Joyce, Improvements in technique at magnetic observatories in the United States of America, Seventh Assembly, Internat. Union Geod. Geophysics, September, 1939.
J. W. Joyce and H. E. McComb, Improvements in methods of field-observations in the United States of America, Seventh Assembly, Internat. Union Geod. Geophysics, September, 1939.
J. W. Joyce, The contributions of research in terrestrial magnetism and electricity to modern communication, Amer. Inst. Mining Metal. Eng., New York, N. Y., February, 1940.
J. Bartels, N. H. Heck, and H. F. Johnston, The three-hour-range index measuring geomagnetic activity, Terr. Mag., v. 44, pp. 411-454, 1939.
H. H. Howe, Magnetic declination in South Carolina in 1935, mimeographed reprinted edition, U.S. Coast Geodetic Sur., 1939.
D. G. Knapp, Practical uses of the Earth's magnetism, serial 618, U.S. Coast Geodetic Sur., 1939.

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IONOSPHERE RESEARCH OF THE NATIONAL BUREAU OF STANDARDS DURING 1939

S. S. Kirby

The program of regular measurements of critical frequencies and virtual heights of the layers of the ionosphere continued throughout the year for frequencies from 600 kc/sec to those above the F_2 critical frequency (maximum, 13,000 kc/sec). Regular publication of these data maintained unbroken the continuity of the National Bureau of Standards' published ionosphere data since 1933. This continuity is important in studying the regular and irregular characteristics of the ionosphere, diurnally, seasonally, and year to year with the sunspot-cycle. The ionization-densities of all the layers of the ionosphere continued to decrease with the waning sunspot-activity. The vertical-incidence ionosphere-measurements were supplemented by oblique-incidence radio field-intensity records of stations on frequencies from 550 to 30,000 kc/sec. The oblique-incidence records gave additional information on maximum usable frequencies, absorption, ionosphere storms, sudden ionosphere disturbances, and sporadic E-layer. They also gave information on the condition of the ionosphere at considerable distances from Washington.

The regular dissemination of information on the ionosphere and on radio-transmission conditions was continued, employing the weekly Ursigrams, Bureau publications, Letter Circulars, reports in Proceedings of The Institute of Radio Engineers, quarterly reports in Terrestrial Magnetism and Atmospheric Electricity, and miscellaneous publications. The monthly reports in the Proceedings of The Institute of Radio Engineers gave the following data regularly: (1) Graphs of monthly average diurnal values of critical frequencies and virtual heights; (2) graphs of monthly average diurnal variations of maximum usable frequencies for radio sky-wave transmission for the second preceding month and predicted values for the month following that of publication; (3) graph showing day-to-day distribution of critical frequency around the monthly average; (4) tables of ionosphere storms, sudden ionosphere disturbances, and, in the summer, sporadic E.

The predicted values under (2) are estimated from a knowledge of the diurnal and seasonal variations and the trend of the critical frequencies with the sunspot-cycle. The prediction and publication of monthly average maximum usable frequencies for undisturbed days three months in advance was pioneered by the Bureau in 1939. This service increases considerably the commercial usefulness of the ionosphere data. The results to date show an accuracy better than 15 per cent.

Under (4), virtual heights and critical frequencies were plotted for 15 ionosphere-storm days. One hundred and twenty-eight days or parts of days of ionosphere storms totaling 1,767 hours were tabulated and rated as to intensity. Seventy-three sudden ionosphere disturbances and 291 hours of sporadic-E layer were reported for the year 1939. These graphs of individual ionosphere-storm days each month, and monthly tables of ionosphere storms, sudden ionosphere disturbances, and sporadic-E layer are continuous since the beginning of 1937. The ionosphere storms were rated as to intensity and the principal characteristics of the several phenomena were given in the tables.

During 1939 the sunspot-activity, and with it the critical frequencies and ionization-densities of the ionosphere layers, decreased. The decrease of critical frequencies was not smooth, even when the seasonal variations were taken out, but had random variations of several

months' duration, above and below the 12-month running average. The critical frequencies for the E-layer were about two per cent below, for the F_1-layer about four per cent below, and for the F- and F_2-layers about nine per cent below, the corresponding values for 1938. The severity and duration of the ionosphere-storm type of disturbance was probably less in 1939 than in 1938, but a series of ionosphere storms which occurred during March and April, 1940, was at least as severe as any observed since 1935 when the Bureau began describing and reporting their detailed ionosphere effects. The number of sudden ionosphere disturbances observed at Washington in 1939 was 73, as compared with 96 in 1938.

The project of automatic recording of field-intensities of European and South American broadcast stations during the winter of 1939-40 was only partially successful on account of the European war; the transmission-schedules of European stations were uncertain and impossible to obtain in advance. An Argentine station was recorded as usual. These records again confirmed the previously reported conclusion that the absorption of night sky-wave at broadcast frequencies was relatively small over the path from Buenos Aires to Washington and that the night absorption over this path and other paths in similar latitudes was little affected by ionosphere storms. This means that absorption below the E-layer is not markedly present at night in low, temperate, and torrid latitudes. An additional important conclusion may be drawn from the cooperative measurements on this project made over several years in Europe, Buenos Aires, and Washington, namely, the law of reciprocity applies to transmissions at frequencies of about 1,000 kc/sec over the paths between western Europe and Washington, western Europe and Buenos Aires, and Buenos Aires and Washington. Transmission was essentially the same in the two opposite directions over each of these paths but not the same over one path as over another.

The Bureau made considerable additions to its ionosphere recording-equipment. The principal addition was a portable multifrequency ionosphere-recorder based on the fundamental principles of the pioneer multifrequency ionosphere-recorder devised and constructed by the Bureau in 1933. The new recorded has speeded up its multifrequency sweeps to one per minute, through the frequency band, 700 to 14,000 kc/sec. The equipment was mounted in a trailer and taken to Fort Clark, Texas, for use during the solar eclipse of April 7, 1940. These observations made there, together with those made at Washington, indicated that the recombination-coefficient of the E-layer was approximately 10^{-8} and of the F_2-layer not more than 10^{-10}.

The following papers were published:

N. Smith, S. S. Kirby, and T. R. Gilliland, Application of graphs of maximum usable frequency to communication problems, J. Res. Nation. Bur. Stan., v. 22, p. 81, 1939.

N. Smith, The relation of radio sky-wave transmission to ionosphere measurements, Proc. I. R. E., v. 27, p. 332, 1939.

J. H. Dellinger, Some contributions of radio to other sciences, J. Frank. Inst., v. 228, p. 11, 1939.

T. R. Gilliland, S. S. Kirby, and N. Smith, Characteristics of the ionosphere at Washington, D.C., published each month in Proc. I. R. E.

Averages of critical frequencies and virtual heights of the ionosphere, observed by the National Bureau of Standards, Washington, D. C., published quarterly in Terr. Mag.

J. H. Dellinger, The role of the ionosphere in radio wave propagation, Amer. Inst. Elec. Eng. Transactions, v. 58, p. 803, 1939.

J. H. Dellinger, The sun and the ionosphere, Fifth Report of Commission on Solar and Terrestrial Relationships, p. 72, published in July, 1939, for presentation at the General Assembly of the International Union of Geodesy and Geophysics held in Washington in September, 1939.

N. Smith, Oblique-incidence ionosphere data and the Lorentz polarization term, Trans. Amer. Geophys. Union, part III, p. 375, 1939.

J. H. Dellinger, Report of Commission II, Radio Wave Propagation, International Scientific Radio Union, Proc. I. R. E., v. 27, p. 645, 1939.

National Bureau of Standards,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF OCEANOGRAPHY

REPORTS AND PAPERS

Washington, D.C.

April 26, 1940

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OCEANOGRAPHIC ACTIVITIES OF THE HYDROGRAPHIC OFFICE AND THE UNITED STATES NAVY DURING 1939

G. S. Bryan

Once again I have the pleasure of reporting to this body on the oceanographic activities conducted by the Hydrographic Office. Investigations and surveys conducted by various United States Naval vessels during the past 12 months have been fruitful in results.

Over 115,000 sonic soundings, mostly over previously unsounded areas, have been obtained by Naval vessels during the past year. I expecto to announce at the 1941 meeting of the American Geophysical Union that all the accumulated sonic-sounding data received in the Hydrographic Office during the past few years, which amount to approximately 300,000 soundings, have been plotted and correlated and that their incorporation on affected charts is well under way. That work in itself will be a great contribution to oceanography and will permit the revision of the bathymetric charts of the oceans by utilizing more authentic and adequate data than have been available in the past. Both the bathymetric charts of the Caribbean Sea and the North Pacific Ocean

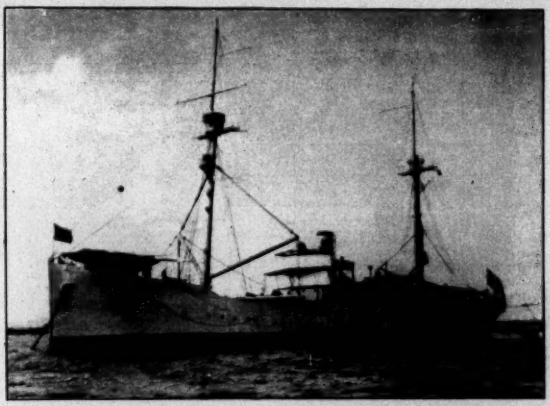

Fig. 1--The U.S.S. Hannibal

respectively have received favorable comment from scientific institutions in this country and abroad. Without the full-hearted cooperation of Naval vessels that, in compliance with plans and instructions furnished by the Hydrographic Office, have striven to utilize every available opportunity to sound in previously unsounded areas, it would have been impossible to undertake the preparation of these bathymetric charts.

The U.S.S. Bushnell, while operating in the Pacific, covered during the season of 1939-40 a total area of 76,000 nautical square miles. The islands surveyed in this area have, due to established commercial air-transportation in the Pacific, increased in importance and, therefore, more adequate surveys were considered warranted.

Some time during this summer, a veteran of the seas will be decommissioned after 42 years of distinguished service with the United States Navy, 28 of which have been spent charting the waters of the Caribbean Sea and the Pacific approaches to the Panama Canal (Fig. 1).

I refer to the U.S.S. Hannibal. It is most fitting that I dedicate part of this paper to a review of the colorful history of that vessel which, while under the cognizance of the Hydrographic Office, conducted vital surveys of the waters adjacent to one of the most important waterways in the world--the Panama Canal.

If we review the hydrographic accomplishments of the Hannibal during the past quarter-century, we will see that the 70 charts produced as a result of her surveys may well be called a

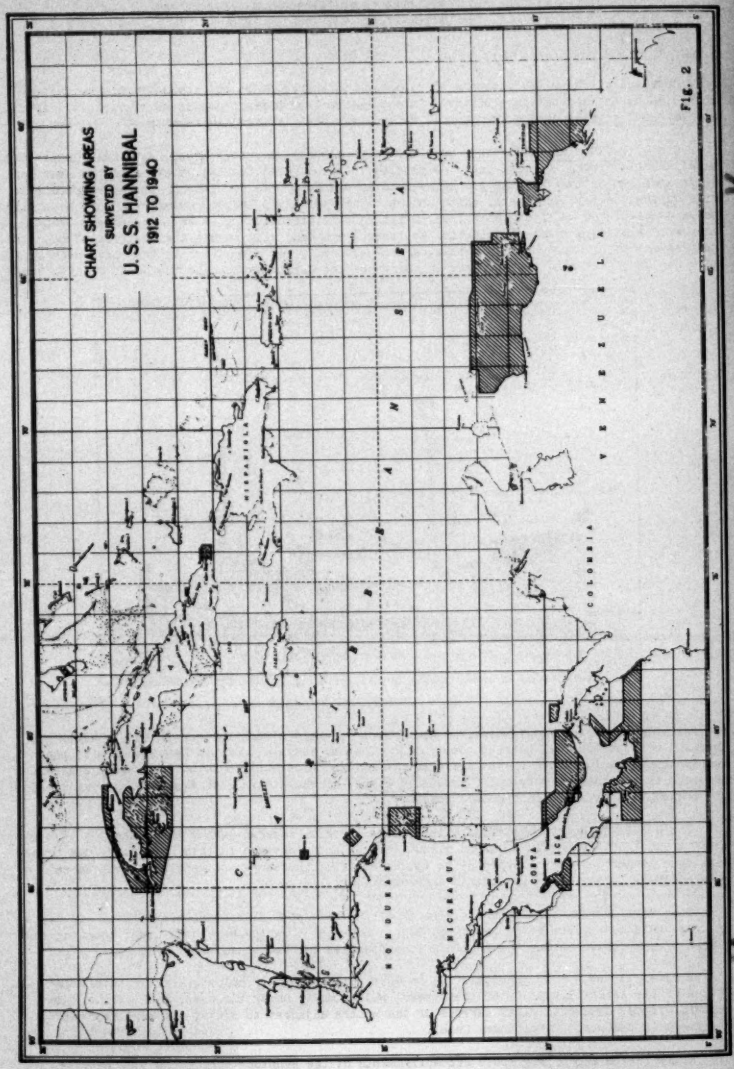
CHART SHOWING AREAS
SURVEYED BY
U. S. S. HANNIBAL
1912 TO 1940
HONDURAS
NICARAGUA
COSTA RICA
COLOMBIA
VENEZUELA

FIG. 2

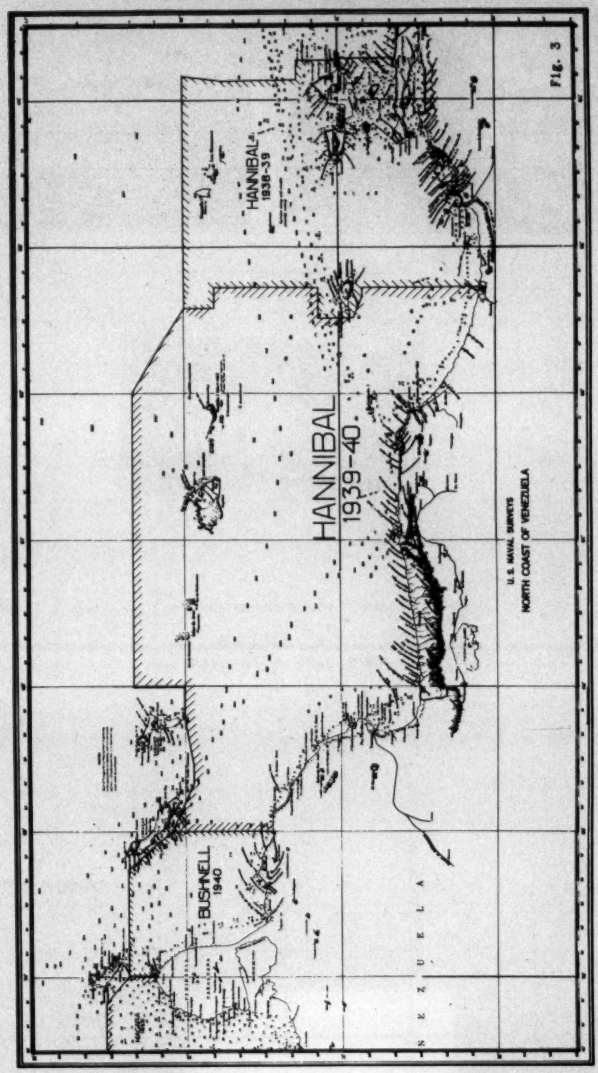
HANNIBAL
1939-40.
HANNIBAL
1938-39
BUSHNELL
1940
U.S. NAVAL SURVEYS
NORTH COAST OF VENEZUELA
VENEZUELA
Fig. 3

Fig. 4

Fig. 5

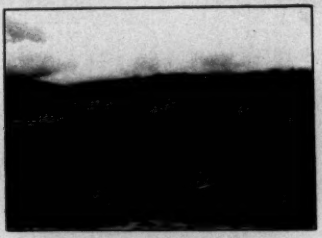

Fig. 6

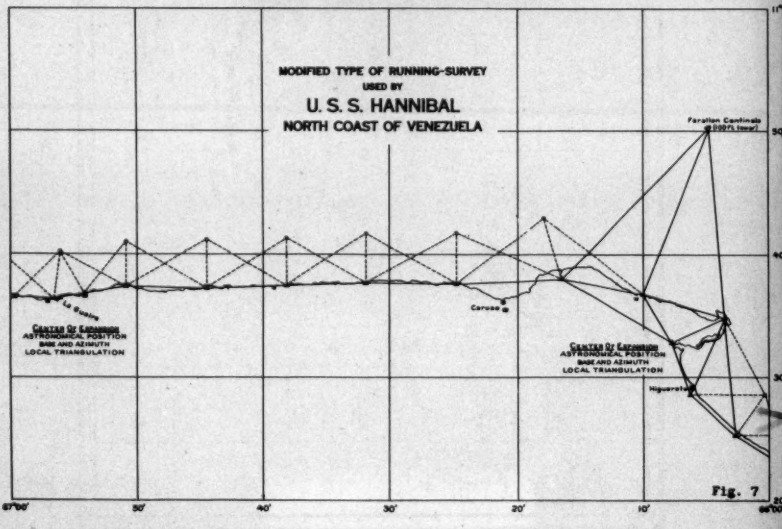

Fig. 7

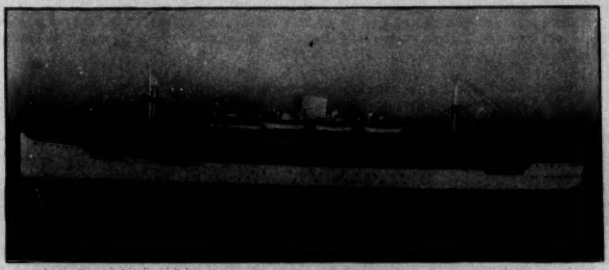

Fig. 8--The U.S.S. Bowditch

Fig. 9--Auxiliary 100-foot boat for hydrographic surveying

lasting monument, not only to the men who lost their lives in the performance of their duties, and to the members of her crew, but also to the gallant vessel which served so long and faithfully in this service.

Panama and Costa Rica (both Atlantic and Pacific coasts), the northeast coast of Nicaragua with its treacherous Miskito Cays, Cuba, and Venezuela, all carry the stamp of the Hannibal which for years ventured through unknown and dangerous waters to safeguard shipping by conducting the surveys which have speeded commerce to the meeting place of the Americas. The fact that Cuba, Panama, and Costa Rica are more completely surveyed than many other countries in the world is due to the work of the Hannibal (Fig. 2).

Soon this ship will be replaced by the U.S.S. Bowditch, but her last two seasons will stand out as her greatest, for, despite old age, the inspiration she has instilled in her officers and crew has enabled them to accomplish the seemingly impossible.

From Punta de Chacopata to Unare, Venezuela, and off-lying islands, the Hannibal last season covered a total area of 8,600 nautical square miles. This season she will complete by June 1940 the stretch from Unare to Punta Zamuro and the off-lying islands of Los Roques, Orchilla, and Aves, a total area of over 20,000 nautical square miles (Fig. 3).

In the prosecution of this work, a modified type of running survey is being employed. Due to the mountainous nature of the terrain, it would have been a very costly and arduous undertaking to extend the triangulation along the coast by using inland stations. The prevalence of clouds over such stations could seriously interfere with the normal progress of the survey if personnel and equipment were delayed for indefinite periods while waiting for suitable observing weather (see Figs. 4, 5, and 6).

In view of the above and due to the nature of the coast, the scarcity of harbors, and the lack of any transportation-facilities along the coast of Venezuela, the following procedure is being utilized during the present season:

Important sections throughout the area are each being controlled by astronomical determinations of latitude and longitude, by a measured base, by stellar azimuth, and by local triangulation of sufficient extent to permit adequate expansion by utilizing the ship as an offshore station. The entire coastal area has been divided into four centers of expansion which serve to adjust the work for base and azimuth at intervals of approximately 60 miles (Fig. 7).

Main and secondary signals are being built over stretches of 40 or 50 miles at a time. At each main station, a repeated angle of one-second accuracy is measured in order to retain azimuth-control along the coast.

With observers stationed at four or five of the mainland triangulation-stations, the ship proceeds to a point offshore, intervisible from at least three stations, two known and one unknown, and lays to at a location so situated as to permit its location to be determined accurately and afford a good cut to the unknown station by simultaneous observations. As all of the shore-parties are radio-equipped, the work of carrying out this system of radio signals sent from the ship is facilitated. The procedure of taking angles from each station to the ship is repeated at least four times before the ship proceeds to a new location in order to afford a check of the computations and to permit ships' observers to obtain the included angles and cuts to intervening hydrographic signals and natural inland objects.

In this manner, it has been possible to extend triangulation for a stretch of about 50 miles in three or four days at very limited expense and within the accuracy specified for coastal surveys.

The U.S.S. Bowditch is at present being fitted out to continue the important job of surveying uncharted waters. Next September, she will sail from Norfolk to undertake, in cooperation with the U.S.S. Bushnell, the hydrographic survey of the Gulf of Guayaquil and the coasts of Ecuador. She is being outfitted with the most modern surveying aids. Amphibian airplanes carried on her deck will permit reconnaissances and photography of the coast to be conducted with a minimum of effort. Radio-acoustic ranging-equipment, taut-wire measuring-apparatus, the latest type of sonic equipment, gyro compass, including automatic steering, radio-direction finder, and ample drafting space, will all facilitate the task assigned to this ship (Fig. 8).

The vessel is 370 feet long and has a beam of 52 feet. Besides carrying out regular survey-work, the ship acts as a floating base for its seven auxiliaries which consist of three 100-foot boats fully equipped for hydrographic surveying (Fig. 9), and four motor sounding-boats of 40- and 50-foot lengths which are carried on her decks. Thus, the Bowditch represents not a single ship but a complete survey-expedition, fully equipped to carry out all phases of the work, and must of necessity be a large vessel self-sustaining for long periods. Her sounding boats will be up-to-date in all respects. Self-recording sonic-depth finders of high accuracy, with a range of 6 to 600 feet, wire-drag gear, radio communication, and living quarters for ten men will be the outstanding characteristics of this new type of sounding boat specially designed by the Hydrographic Office for hydrographic surveying.

It is our aim to make the Bowditch a model hydrographic and oceanographic survey-vessel. Her size and cruising radius are important factors in the type of surveying work conducted by the Hydrographic Office where the base of supplies is far distant from the scene of operations. It is my sincere hope that eventually funds will be made available to install a complete oceanographic laboratory aboard the Bowditch to permit extensive oceanographic research to be conducted in connection with the hydrographic work. Such oceanographic research is much needed and every effort should be made to make it possible.

During the past year the U.S.S. Bushnell occupied 18 dynamic stations on two lines, one between the Panama Canal and San Diego, and the other between San Diego and the Hawaiian Islands. A representative of the Scripps Institution of Oceanography accompanied the Bushnell to San Diego and greatly assisted in the work. It is planned to transfer all dynamic gear to the U.S.S. Bowditch prior to the coming season.

The project for evaluating ocean-current and sea-surface temperatures for all oceans of the world, covering a 30-year period, is rapidly being completed. All tabulation-work has been finished and monthly temperature-charts of the Pacific have been compiled. However, due to the great increase of chart-printing, consequent upon the outbreak of war in Europe, the publishing

of this material has been delayed but the completed temperature- and current-charts will appear as opportunity affords.

In connection with the United States Antarctic Expedition, the Hydrographic Office has cooperated by constructing two large-scale charts to be used in establishing bases in the Antarctic Continent and making available surveying instruments and numerous charts and publications required for the cruise. An oceanographic program, which is part of the scientific work to be conducted by the Expedition, was specially prepared by the Hydrographic Office. Recent reports indicate that much valuable information has already been obtained by the Expedition.

The cooperation the Hydrographic Office has always given and received from mariners throughout the world, and from scientific and governmental institutions in the United States and abroad, is a source of satisfaction not only to me but to the entire personnel of the Office as well. You may be assured that the Hydrographic Office will always consider it a privilege to assist the American Geophysical Union and its members as well as all other Government and scientific institutions in the furtherance of oceanography.

Hydrographic Office,
U. S. Navy,
Washington, D. C.

OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD IN THE WESTERN NORTH ATLANTIC IN 1939 AND PLANS FOR 1940

R. R. Waesche

During the 1939 ice season the United States Coast Guard cutters Chelan and Champlain were assigned as patrol-cutters to conduct the International Service of Ice-Observation and Ice-Patrol. The 125-foot patrol-boat General Greene was again assigned as the oceanographic vessel of the Ice-Patrol Force. The ice-observation officer, who has charge of the scientific work on the patrol-cutters, was Lieutenant W. P. Hawley, and the oceanographer in charge of the scientific work on the oceanographic vessel was Floyd M. Soule.

The patrol-cutters made 11 cruises of about two weeks each in the region of the Grand Banks of Newfoundland between March 9 and August 23. From data collected on these cruises, 11 fortnightly sea-surface isothermal charts were prepared and will be published in United States Coast Guard Bulletin No. 29. The ice-patrol was discontinued on August 23, the latest date in the history of this international service.

During the months of April, May, and June the General Greene supplied the patrol-cutters Chelan and Champlain with dynamic topographic charts of the Grand Banks region. Four current-surveys were made during this period. The resulting charts were referred to the 1,000-decibar surface although at most of the oceanographic stations the temperature- and salinity-measurements extended to a depth of about 1,400 meters where the depth of water permitted. It was hoped that during the third cruise a somewhat smaller than usual area could be surveyed and then immediately remapped in an attempt to learn more of the rapidity with which the current-patterns change. However, because of the spread of menacing ice in the critical area, it was necessary to apply the time available to a single survey.

In operating this map-service 201 oceanographic stations were occupied. Between July 10 and July 15 the General Greene occupied 25 additional oceanographic stations, from the surface to as near bottom as was practicable, on an abbreviated post-season cruise in the Labrador Sea. The stations on this cruise were disposed in the form of a single section from South Wolf Island, Labrador, to Cape Farewell, Greenland.

United States Coast Guard Bulletin No. 28, by Floyd M. Soule and G. Van A. Graves has just appeared in print. In it are discussed the results of the 1938 season and post-season cruises. Bulletin No. 29, by Hawley and Soule, is now in press. This Bulletin deals with the results of the work in 1939 which has been outlined here. The oceanographic section of this Bulletin is summarized as follows:

(1) Four current-surveys of the Ice-Patrol Area in the vicinity of the Grand Banks, made during the 1939 season, have been described.

(2) Computations of the volume of flow have been made and the results presented to show the

seasonal variation of the Labrador Current during 1939 as compared with other variations found during the previous five ice-seasons.

(3) The boundary between Atlantic-Current water and Labrador-Current water, as delineated by the horizontal projection of the zero-salinity-anomaly surface at the intermediate salinity-anomaly maximum, was investigated but found to be outside the limits of the surveys of 1939.

(4) Profiles of temperature- and salinity-anomaly near the Tail of the Grand Banks have been used to clarify the genesis of the isolated cold-water masses frequently found in that vicinity, and incidentally to point out a partial cause of the intermediate salinity-anomaly maximum.

(5) A recapitulation of the various indicators of the shape and depth of the motionless surface in the Grand Banks Region has been given and amplified by a further verification in the form of a deep-level isentropic analysis of data collected on the 1937 post-season cruise.

(6) Tables of the difference between σ_0 and σ_t for various values of temperature and density, and of σ_0 corresponding to various values of salinity have been given to facilitate the plotting of lines of equal σ_t on temperature-salinity coordinates.

(7) An analysis of the first survey showed the existence of definite temperature-salinity correlations for the mixed water and Labrador-Current water in the Grand Banks Region, and the correlations have been presented graphically.

(8) A comparison between the thermal characteristics of the Labrador Current off South Wolf Island, Labrador, found in 1938 and 1939, has been presented to show the offshore shift of this current resulting from abnormal winds during the winter of 1938-39, and to point out the effect on the mortality of bergs en route to the Grand Banks.

(9) The volume of flow, mean temperatures, and heat-transfers of the Labrador Current at South Wolf Island and of the West Greenland Current at Cape Farewell, have been derived from observations made in 1939 and compared with seven previous occupations of the Labrador Section and nine previous occupations of the Cape Farewell Section. Results have been tabulated and particular emphasis placed on the seasonal variation of the temperature of the West Greenland Current in the interpretation of these results. Taking account of this seasonal variation a negative correlation has been found to exist between the mean temperature of the West Greenland Current and its volume of flow with the conclusion that fluctuations in its volume of flow arise chiefly from fluctuations in the East Greenland Current.

Oceanographic work planned for 1940 has already begun. The first survey of the Grand Banks Region was completed on April 9 and the second survey is now in progress. The General Greene is again providing a map-service for the patrol-cutters Chelan, Cayuga, and Pontchartrain which have been assigned for this year's patrol. We hope that during this season there may be the opportunity, denied us last year by the disposition of the ice, to make a quickly repeated survey of at least a portion of the Grand Banks Region. Present plans contemplate a post-season cruise by the General Greene in the Labrador Sea at the conclusion of the ice-season. This cruise will include an oceanographic section from southern Labrador to Cape Farewell, Greenland, and such other observations pertaining to ice-movements as the conditions then existing may permit.

U. S. Coast Guard,
Washington, D. C.

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

L. O. Colbert

As in past years, the oceanographic activities of the United States Coast and Geodetic Survey have been concerned primarily with the delineation of the ocean's bottom in areas surrounding the United States and its possessions. This task is necessarily supplemented by the measurement of tides and currents in order to obtain accurate values for the reduction of observations, and these data, combined with similar observations from numerous other points, become the basis of a second major oceanographic function of the Bureau, that is, the prediction and publication of the times and heights of the tides and of the strength and direction of the currents.

Of further interest to the oceanographer, and a necessary by-product of our offshore surveys, are the temperature- and salinity-observations taken to determine the velocity of sound in

sea-water. An accurate value of this velocity is required for each area in which depths are measured by echo-sounding methods or positions are determined by radio-acoustic ranging.

In addition to these basic activities the Coast and Geodetic Survey often has found it possible to cooperate with other Government organizations and with scientific societies in the collection of bottom-specimens and water-samples. During the season of 1939 the survey-ship Hydrographer furnished the Houston Geological Society 150 bottom-specimens obtained over a wide area in the Gulf of Mexico. These specimens, notable for their large content of microscopic fossils, proved particularly important in investigations for oil-deposits.

During the present fiscal year our mapping program has been accelerated by increased appropriations which permit the nearly continuous operation of our survey-vessels. It has now become possible to supplement the summer season in northern waters with a short winter season in workable areas farther south.

Two new ships of the most modern type were added to the survey-fleet in the spring of this year. The Explorer, a 220-foot vessel powered by a 2,000-horse-power steam-turbine, has a cruising radius of 8,000 miles and was designed especially for long voyages in isolated waters. The E. Lester Jones is a sturdy 88-foot wooden tender built for work in the more protected areas. Both vessels will be assigned to surveys off the Aleutian Islands during the coming season.

The routine prosecution of our offshore surveys often results in findings of unusual interest. During the summer of 1939 the survey-ship Oceanographer discovered many large and remarkable sand-waves in the vicinity of Nantucket Shoals and obtained a number of profiles by a recording echo-sounder. The sand-waves are in some cases as high as 60 feet and extend 2,000 feet from crest to crest. The crests generally trend normal to the predominating tidal current, and vary in form from the progressive type to purely symmetrical waves. They are found in depths between four and 30 fathoms and appear to be peculiar to areas in which strong tidal currents exist.

In the development of the water-areas east of Cape Romaine, South Carolina, indications of the ancient mouth of the Santee River were found on the continental shelf some 80 miles offshore by the Oceanographer. This same party made the unexpected discovery that during the past winter, between the months of October and March, in the area east of Cape Romaine no northerly surface-currents existed in what has been charted as the axis of the Gulf Stream and the area of maximum current. Increases in the water-temperature were observed as the supposed axis of the stream was approached but there was no appreciable increase in salinity. Northerly winds prevailed during this period of observation.

While en route to San Francisco from Alaska the ship Pioneer found a submarine peak of impressive proportions 130 miles west of Cape Mendocino, California. The summit, 4,300 feet below the surface, drops off 10,300 feet to the southeast in a distance of ten miles, and 6,500 feet to the northwest in the same distance.

In the Gulf of Alaska two submarine mountain formations of unusual interest were discovered. One, rising 9,500 feet from the ocean-floor, lies about 200 miles south of Kodiak Island. Preliminary soundings taken by the survey-ship Surveyor indicate that the base of the mountain measures more than 14 miles in width and that its top reaches to within 4,700 feet of the surface of the water. Similar under-water formations have been discovered in nearby Alaskan waters in recent years, but none so impressive in its sheer rise from the ocean-bottom. Until further investigation is made it would be useless to speculate on the extent of these mountains, but the possibility does exist that the area is an under-sea replica of the giant peaks that form the nearby Alaskan Peninsula.

The second under-sea mountain or mountain range in the Gulf of Alaska was found by the survey-ship Guide about 350 miles west of Cape Flattery on the Washington coast. The formation rises 9,800 feet from a base 23 miles in width and reaches to within 2,600 feet of the surface. When more fully surveyed these distinctive formations will serve as valuable location-marks to transpacific vessels equipped with echo-sounding devices, equally as reliable as landmarks ashore.

A general summary of our activities and plans can best be given by a brief résumé of the work of our survey-vessels. Along the Atlantic Coast the Oceanographer and Lydonia completed the offshore project which extends beyond the limits of the continental shelf from Georges Bank to the Virginia Capes, and during the past winter season began a smiliar project off North and South Carolina which will extend to the Virginia Capes on the north and to the Florida Keys on the south. Both vessels will be engaged during the coming summer on the survey of the Gulf of Maine from Boston Harbor to Georges Bank and Nova Scotia. The motor vessel Gilbert continued

the survey of Nantucket Sound. During the next season this vessel will be engaged on a survey for the development of Nantucket Shoals.

In the Gulf of Mexico the Hydrographer completed offshore soundings along the Texas coast to the Mexican border and has shifted operations to the central and eastern parts of the Gulf. With one major vessel continuously engaged on the work the offshore surveys of the entire Gulf should be completed by 1947.

On the Pacific Coast the Guide was engaged during the fall and winter in work off Cape Mendocino, California. Other major units made revision-surveys of San Francisco Bay, Grays Harbor, and the northern end of Puget Sound.

The motor-vessel Westdahl continued surveys of Glacier Bay, Southeast Alaska. This project, begun in 1938, will continue through the next two years.

During 1940 the survey-vessel Surveyor will begin operations on the eastern end of a project of original surveys of the Alaskan coast between Cape Fairweather and Cape St. Elias. It is expected that this season's work will extend from Lituya Bay to Dry Bay.

Since 1934 the Coast and Geodetic Survey has been engaged on the original basic survey of the Alaskan Peninsula and the Aleutian Islands. This difficult and hazardous project, of paramount importance to commercial navigation as well as to the national defense, has progressed satisfactorily and, unless it becomes necessary to reduce the present force of four major and two auxiliary vessels assigned to that area, should be completed in about six years. The magnitude of the undertaking may be visualized when one realizes that the Aleutian Islands extend over 1,000 miles westward from the western end of the Alaskan Peninsula and approach to within 250 miles of the islands off the Siberian coast.

During the past season the Guide extended surveys eastward on the Bering Sea side of the Alaskan Peninsula and will continue this work during the coming season. The Discoverer will continue work on the south side of the Peninsula which will eventually join with the recent surveys which have been extended from Prince William Sound to the southern end of Kodiak Island. On the south side of the Aleutian Islands the Pioneer has completed surveys to Yunaska Island and will continue in this area. The new Explorer, in cooperation with the E. Lester Jones, will work on the north side of the Aleutian Islands westward from the Islands of Four Mountains.

En route to and from the southwestern Alaskan area, sounding lines are run each year across the Gulf of Alaska by the survey-vessels. To date 38 such lines have been surveyed and five more are contemplated for the present year. These lines furnish practically the only knowledge we have of the configuration of the Gulf and when more widely extended will undoubtedly prove a source of particular interest to the geologist as well as to the oceanographer.

No additional work was done in the Hawaiian Islands in 1939 and none is contemplated for 1940.

In the Philippine Islands the Pathfinder continued surveys on the west coast of Palawan and the Fathomer began operations in the area between Balabac and Cagayan Sulu. The original basic surveys of the Philippine Islands are now complete with the exception of a 70-mile stretch off the west coast of Palawan and an area in the southwestern Sulu Sea adjoining the waters of British North Borneo.

In the field of tides and currents, present-day problems demand comprehensive surveys specially planned with a view to meeting present and future needs in the widening fields of engineering practice and scientific research. Recognizing the importance of systematic observational data, the Coast and Geodetic Survey has developed a framework of primary tide-stations in the maintenance of which precision and continuity of operation are emphasized. These stations, if continued in operation and extended as planned, will in the future furnish information on sea-level trends and geological changes in coastal areas which is denied to the oceanographer and geologist of today due to lack of similar records during past periods.

To avoid duplication of effort the Coast and Geodetic Survey is utilizing the facilities of other interested agencies by cooperative arrangements for obtaining observational tide- and current-data. Of the 81 primary and secondary tide-stations in operation by the Coast and Geodetic Survey at the present time, 39 are maintained on a cooperative basis with various federal, state, county, and municipal agencies, as well as with private interests, port-authorities, and oceanographic institutions. Outstanding among the organizations that have rendered cooperation

are the United States Army Engineers, the United States Navy Department, the United States Coast Guard, the Scripps Institution of Oceanography, the Oceanographic Laboratories of the University of Washington, the Chesapeake Biological Laboratory, and the Woods Hole Oceanographic Institution.

Through the continued cooperation of the United States Coast Guard, a series of hourly current-observations covering a period of 13 months was completed at Fire Island Lightship in the approach to New York Harbor. Similar observations covering a number of months were secured at Overfalls Lightship in the entrance to Delaware Bay. These observations, together with shorter series taken at a number of locations by hydrographic parties and in cooperation with other organizations, will be incorporated in the current tables, tidal current charts, and special publications of the Bureau. There is now in preparation a new publication of tidal current charts which will cover the waters of Narragansett Bay, Buzzards Bay, Vineyard Sound, and Nantucket Sound.

In closing, I would like to thank those organizations that have continued to lend us their valuable assistance, and to assure you that we shall welcome the opportunity to make available to members of the Union the results of the data accumulated in the course of the various activities of the United States Coast and Geodetic Survey.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1939 TO APRIL 1940

H. U. Sverdrup

(Contribution from the Scripps Institution of Oceanography, New Series, No. 94)

Emphasis will again be placed on the activities within the fields of submarine geology and physical and chemical oceanography, although researches within the biological fields cover the greater part of the work at the Scripps Institution of Oceanography. The compilation and discussions of field-data and the studies in the laboratory have been greatly facilitated by assistance obtained from the Works Progress Administration Project No. 665-07-3-141.

As previously, the sediments-laboratory has made a large number of mechanical and partial chemical analyses of sediment-samples in the collections of the Scripps Institution. In approximately 50 cores collected on the 1939 cruise of the vessel E. W. Scripps to the Gulf of California the particle-size distribution and contents of calcium carbonate, organic nitrogen, water, and chloride have been determined at a series of ten or more depths within each core. Likewise, representative portions of the sediment-samples collected in 1938 under the direction of F. P. Shepard have been analyzed, together with cores collected during the present year off the Lower California coast and in southern California waters by Revelle. The analytical work has been supported in part by a grant from the Geological Society of America and by other funds from outside sources, while the making of such a large number of analyses has been possibly only because of technical assistance supplied by the Works Progress Administration.

Besides the above studies of the relationships between certain sedimentary characteristics and environments of deposition, considerable attention has been directed during the past year to investigation of sedimentary processes, particularly to problems of transportation of debris in the sea and to physical and biochemical processes in sediments after deposition.

Problems of sediment-transportation may be conveniently divided into two categories, namely, the nature of transporting agencies, and the character of transported materials. In collaboration with Carl Johnson, a tripod has been developed containing three Ekman-type current-meters arranged one above the other, by which it has proved possible to measure the vertical distribution of velocity within a meter of the sea-bottom in waters of considerable depth, without anchoring the ship. Six series of measurements for periods greater than 12 hours have been made in a variety of environments, including offshore banks, the mainland shelf, and the deep Santa Monica and Santa Cruz basins. An unexpected feature of the results was the observation of velocities up to 15 cm/sec at the bottom of the Santa Cruz Basin in waters 1,900 meters deep and nearly 1,000 meters below the sill depth of the Basin.

With the aid of a grant of funds from the American Association of Petroleum Geologists, studies of the character of transported materials are being carried out by means of sediment-

traps near the bottom. The relative efficiency of different types of traps in capturing the sedimentary load of moving waters is being investigated as a fundamental part of this work, which is being carried on in collaboration with F. P. Shepard and K. O. Emery. In the laboratory, studies of the process of coagulation of colloidal suspended materials by salts in seawater have been made in cooperation with Mrs. Lois Sorkness. It has been found that the degree of coagulation varies directly with the concentration of suspended material, as well as with the concentration of dissolved salts.

Problems of physico-chemical and biological equilibria in marine muds have likewise been approached from several different aspects. Investigations of the distribution and activities of aerobic and anaerobic bacteria in cores have been made by S. Rittenberg, who has also measured by means of a glass electrode the vertical distribution of pH in freshly-collected cores of various types. Relative high pH-values, well over 9.3, have been observed in calcareous cores at depths of 100 or more centimeters beneath the surface, while values as low as 7.4 have been found in highly organic sediments. An attempt has been made to determine the amounts of iron sulfide in muds of different environments, but in only a few cases have determinable quantities been detected, even where H_2S was obviously present. In connection with studies of the sulfur cycle in marine muds a conductiometric titration-method for the determination of sulfate, chloride, and other dissolved salts in sea-water and in interstitial waters of marine sediments has been developed, chiefly by L. J. Anderson.

E. C. La Fond has had supervision of an instrument for recording wave-heights and periods and of a current-meter, both at the end of the Institution's pier, and has obtained daily records whenever weather-conditions permitted. He has taken soundings and other observations on the beach weekly at the Scripps Institution pier, the Del Mar pier, and Crystal pier, the number of soundings totaling about ten thousand.

Owing to greatly reduced clerical help, averaging and plotting by months and quadrangles of sea-surface temperatures reported to the Scripps Institution by navigators of steamers in the Pacific Ocean continued only till August, 1939.

The Works Progress Administration project, sponsored in 1935 by the University of California for compiling oceanographic data reported by navigators of all ships in the Pacific to the United States Hydrographic Office from 1904 through 1934, was completed late in the summer of 1939. All of the coding sheets (about 60,000), containing data from the Pacific Ocean, are now on file at the Scripps Institution for use in studies of ocean-surface conditions--in particular, the seasonal and yearly variations of surface-currents in the Pacific Coastal region of California. Progress in compilations begun in August, 1938, from the coded sheets to forms designed for the above studies was interrupted in August, 1939, because of reduced clerical help.

Because of continued interest evidenced by correspondence with many individuals and representatives of various organizations, the usual work of providing advance indications of air- and sea-temperatures and seasonal precipitation of Pacific coastal areas was done. As usual, advance indications were mimeographed in October for our mailing list and for the press. Mr. Gordon has made some progress in revising his preliminary approach to problems of rainfall-cycles. The improvement involves random variations in phases which, for predicting, has the advantage over the ordinary Fourier development that the quantities are given directly in terms of observations up to the time of prediction. The United States Department of Agriculture has continued for several years a critical examination of various long-range forecasting methods in use and has carried on special investigations of the forecasting problem. Quite properly a Government agency should ultimately provide such forecasts. Long-range forecasts even approximating to the high standards being realized in those for short periods necessarily involve world-wide observations and solutions of various complicated meteorological problems. Their realization requires an extensive cooperative undertaking and no agency is better equipped for this than the Weather Bureau. Meanwhile, even the very meager service now being rendered by other agencies will likely continue in response to immediate requirements.

Since November, 1939, when the Polish climatologist, Dr. W. Gorczynski, began working at the Scripps Institution on his studies of comparative climates of California and other Western States with sunny regions of Europe and Africa, most of the time and facilities of one division have been devoted to his climatic studies. This has involved a large amount of compilation and computing and the preparation of many charts at a time of great reductions in clerical and other help. McEwen has collaborated in these climatic studies and has worked out certain technical problems of a statistical nature whose solution was needed. In particular, these problems have been concerned with erros and standardization of the precipitation-ratio, and will be prepared for publication. Among various proposed publications based upon Dr. Gorczynski's climatic in-

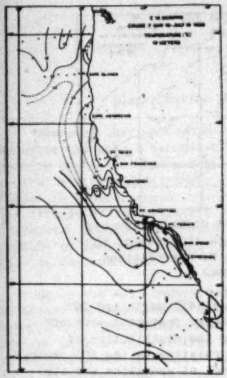

Fig. 1--Temperature-distribution off coast of California at depth of 10 meters, according to observations May 10 to July 10, 1939

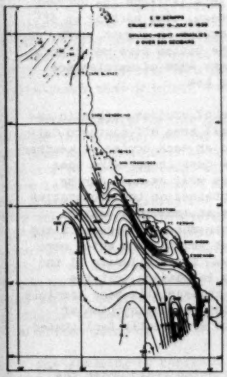

Fig. 2--Dynamic topography of sea-surface off coast of California relative to 500-decibar surface, according to observations May 10 to July 10, 1939

vestigations is a somewhat popular small book on "California's sunny climates."

While not bearing directly on oceanography or the problem of long-range forecasting, this investigation involves the "field" rather than the laboratory point of view and should be a valuable supplementary undertaking.

In order to facilitate numerical applications of statistical methods that he has devised and published for estimating the densities of bacterial populations in solutions, Mr. Gordon has prepared a five-page paper entitled "A shorter method of computation of the estimate of the mean and variance," which will serve until appropriate tables have been computed.

A problem arising in McEwen's formula for computing surface-currents from temperature, referred to in the report of 1939, of estimating the error of a quotient, has been worked out by Mr. Gordon. Extensive applications of the formula have been made to North Pacific Observations and the results are being assembled for publication.

Computations of turbulence and vertical velocity have been made from numerous sets of serial temperatures and salinity-observations within ten miles of La Jolla and at various months within a ten-year period. Methods of computation developed earlier were used.

Mr. Gordon, as a result of studying an earlier (1929) publication of McEwen's on a theory of the vertical distribution of properties in a body of water, has made further progress in developing a more fundamental method, using a turbulence-coefficient varying with the depth and assuming that energy is dissipated at a rate proportional to this coefficient. His results do not seem too complicated for numerical application to ocean-observations.

Methods developed earlier have been applied to various types of problems involving the dispersion in three dimensions of suspended material concentrated near shores and settling at a constant rate.

E. G. Moberg and his assistants have devoted much time to routine work in connection with the cruises of the E. W. Scripps. During the past year several hundred water-samples have been analyzed for calcium. These comprise samples from the Gulf of California, from the local areas which are now being investigated, from the long summer cruise of 1939, and from the Bushnell stations between San Diego and Panama. The results of all these analyses are now being studied. Whether they will be worth reporting upon is yet to be decided.

On the cruises in progress the distribution of phosphates is being examined at various depths and promising results are accumulating. The nitrogen in all bottom-samples obtained in the Gulf of California has been determined and these analyses have produced significant results. John Lyman is engaged in experimental work bearing on the carbon-dioxide equilibrium in sea-water.

The data from the cruise to the Gulf of California between February 5 and March 31, 1939, which was mentioned in last year's report, have been compiled by H. U. Sverdrup and R. H. Fleming, and a discussion of the major features of the physical and chemical characteristics of the waters of the Gulf was presented at the meeting of the International Association of Physical Oceanography in September, 1939.

Between May 10 and July 10, 1939, a cruise off the California coast was made in cooperation with the Federal Bureau of Fisheries. On the cruise 77 stations were occupied, most of them

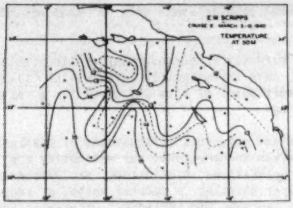

Fig. 3--Temperature-distribution off southern California at depth of 50 meters, according to observations March 5 to 15, 1940

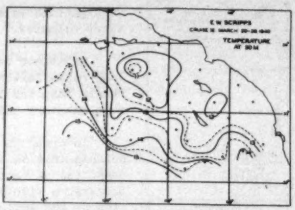

Fig. 4--Temperature-distribution off southern California at depth of 50 meters, according to observations March 20 to 28, 1940

lying along six lines extending from points on the coast betwen latitudes 45° north and 25° north to distances of 300 to 350 miles from the coast. Unfavorable weather prevented work off the coast between Point Reyes and Cape Mendocino. Figures 1 and 2 show the distribution of temperature at a depth of ten meters and the topography of the surface relative to the 500-decibar surface. The distribution of temperature clearly demonstrates the effect of upwelling and also shows a tongue-like distribution of temperature off southern California similar to the one which was observed on cruises in that area in 1937 and 1938. The chart of the topography of the surface demonstrates the character of the California Current and the existence of the previously observed eddy off the coast of southern California. The character of the water-masses along the southern lines of stations off Cedros Island (latitude 28°) indicates a transition to the subtropical waters of the Pacific. It is probable that shortly south of this latitude the current turns west and joins the north equatorial current across the Pacific Ocean. The working up of the data of the cruises has been conducted by Richard Tibby. After a cruise in August, 1939, on which cores of sediments were procured and current-measurements near the bottom were undertaken, the E. W. Scripps was laid up until the end of February, 1940. Necessary work of maintenance was completed including installation of new batteries and change of the bow.

On March 5, 1940, the E. W. Scripps left for the first of a series of cruises, again in cooperation with the Federal Bureau of Fisheries. On these cruises a small area off southern California will be examined in detail. Up to 40 stations will be occupied on each cruise if weather-conditions permit, each cruise lasting ten to twelve days. After a few days in port the same stations will be reoccupied and it is expected that at least six cruises will be made during March, April, May, and the first half of June. By means of the data obtained on the consecutive cruises it is hoped that it will be possible to derive the trajectories of individual water-masses and study the changes in populations which occur within such water-masses. Figures 3 and 4 show the temperature-distribution at a depth of 50 meters on the first two cruises which were completed between March 5 and 15 and March 20 and April 5, respectively. The similarity of the two pictures is striking but certain systematic differences can be seen indicating that the density of the network of stations and the short time-interval between cruises will make possible the hoped-for analysis. The compilation of the data is in progress under the supervision of R. H. Fleming. The calculations of specific volumes and dynamic heights are greatly facilitated by new tables which have been prepared by E. C. La Fond.

A new series of publications from the Scripps Institution has been established under the title "Records of observations, Scripps Institution of Oceanography." The first number of this new series will appear shortly and will contain the oceanographic observations made on the six cruises of 1938 with preliminary discussions. It will also contain a complete description of the research-vessel E. W. Scripps of the Institution. The second number will contain the oceanographic observations which were made in 1939, but the preparation of the manuscript has been delayed owing to a temporary interruption of the assistance rendered by the Works Progress Administration. The new series will be printed in offset by the University of California Press.

Scripps Institution of Oceanography,
University of California,
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THE NECESSITY OF A NEW APPROACH TO THE STUDY OF THE CIRCULATION ON THE CONTINENTAL SHELF

C. O'D. Iselin

(Contribution No. 258 of the Woods Hole Oceanographic Institution)

Wherever the continental shelf is at all wide and provided there is sufficient river-water entering the sea, a current-system develops parallel to the coast due to the relatively low density of the inshore waters. These currents, which are here called coastal currents, have several striking differences from the type of flow found offshore in deep waters. In the first place, in typical areas inside the 100-fathom curve the salinity increases with depth, which is the reverse of the situation found in most deep, oceanic areas. Moreover, the vertical and horizontal gradients of salinity often outweigh the temperature-distribution in determining the pattern of density. In most coastal areas the density-distribution is the cause and not the result of the currents.

As is now well understood, the Circulation Theorem of Bjerknes can be applied to any type of steady current-system, whatever its cause. Thus in analyzing dynamically the flow near the edge of the continental shelf, where the coastal type of current is often parallel and in close contact with an oceanic type of movement, one does not have to take into account that offshore the distribution of density is the result of the movement while inshore it is the cause. However, it is becoming increasingly clear that only in the case of quite strong coastal currents does the ordinary application of the Circulation Theorem give a reasonably correct picture of the current-pattern.

There are several well-known reasons why one should be distrustful of weak current-patterns derived from the dynamic analysis of a network of stations made on a wide continental shelf. Not only are the complications resulting from short-period interval waves often particularly troublesome, but in many areas the velocity of the tidal currents far surpasses that of the gradient-flow, so that the assumption of a steady state of motion is most questionable. In addition, the relatively great difference in depth from station to station introduces a difficulty which cannot be solved in a satisfactory manner. It is perhaps for these reasons that during recent years some physical oceanographers have preferred to study currents in deep water.

Unfortunately for the physicist, who finds that the oceanic currents still provide plenty of food for thought, the marine biologists have their main interests in the shallow seas which are much more productive in the commercial sense. Any fisheries-research program is greatly facilitated by a knowledge of the current-pattern in the area under investigation and at present there is no single reliable method for obtaining this information, unless the currents are strong. The productive fisheries are often located in areas of relatively weak gradient-flow. This is very much the case with Georges Banks, now being intensively investigated by the biologists of the Woods Hole Oceanographic Institution. In this area it seems nearly hopeless by the ordinary water-bottle technique to secure physical observations which will provide information on the currents to supplement the biological surveys. Moreover, as is so often the case in fisheries-investigations, the physical observations must be secured as rapidly as possible and for the most part at points selected by the biologists. Working from a single ship it is nowadays most difficult to combine both physical and biological observations into a survey which is satisfactory from either point of view.

But assuming no conflict with biological requirements, how can one learn about the movements prevailing in such an area as Georges Banks? At the present time we have three well-tested techniques, namely, water-bottle observations, current-meter measurements, and drift-bottle experiments. None of them provides the sort of information which is really most needed.

Because laterally the temperature-salinity correlation changes so rapidly in many coastal areas, it seems clear that the cross-current components are often relatively strong. On a fishing bank, where the gradient-flow usually is peripheral (clockwise around the edge of the bank in the Northern Hemisphere), the cross-current transfer is much more significant biologically than the more obvious flow at right-angles to the pressure-gradient. The cross-current components primarily supply sufficient salt to the waters over the continental shelf to counteract the diluting effects of land-drainage. In many coastal areas this is no insignificant amount. Typically the relatively saline offshore-waters penetrate landwards along the bottom, especially along gullies and drowned river-valleys, while at the surface fresher waters escape offshore. For the New England region, the land-drainage figures and the vertical salinity-gradient over the continental shelf indicate that roughly 15 per cent of the waters of the whole Gulf of Maine

must be renewed each year by inflow from offshore along the bottom. Near the outer edge of the continental shelf the renewal may well be more rapid than close to the shore. It seems likely that the interchange between Georges Banks and the surrounding seas proceeds at an average rate of as much as ten per cent per month. In this case the cross-current components are perhaps mass-movements and not the sort of lateral frictional transfer visualized under the theory of isentropic mixing.

From the biological standpoint it is clearly desirable to learn as much as possible concerning the cross-current components of coastal circulation. From the physical point of view also, these probably constitute the most promising clue to the circulation-problem in coastal areas. It will be of great interest to learn not only the amount of lateral transfer, but also how much of it can be accounted for by frictional forces and how much by actual mass-movements in the direction of the Archimedian force. The latter are of course to be expected, if the flow is not steady in the sense required by the Circulation Theorem.

As mentioned already, coastal circulation is in many areas characterized by strong tidal oscillations. Thus in examining the mixing processes the observer should not remain in the same geographical position, but should move with the water-mass being studied. It seems probable that a profitable method of attack might involve the use of a marker-buoy which would allow the research-vessel to follow the changes of the temperature-salinity correlation in a given mass of water near the boundary between the coastal water and the offshore water. This buoy could be anchored by a drag to whatever layer is desired. Its movement across current from day to day would be a measure of the mass lateral transfer, while the repeated water-bottle observations near the buoy might provide data on the coefficients of lateral and vertical turbulence.

It seems possible that in certain cases two or more such buoys, each anchored to different subsurface layers, might provide relatively exact measurements, even though the lateral mass-transfers were quite slow. Easy and accurate repeated measurements can be made of the distance apart and bearing of a pair of floats. Likewise, the movements of these floats anchored to various subsurface layers can be measured relative to a float anchored to the bottom.

This is the sort of information needed by biologists to understand the dispersal of fish eggs and the movements of the plankton. It would, I believe, also greatly assist the physicists in understanding the nature of the current-system in regions where there is reason to doubt the applicability of the ordinary dynamic technique.

Besides the more or less steady interchange between the relatively fresh waters on the continental shelf and the more saline offshore-waters, it seems likely that from time to time, either because of the winds or because of the formation of large frictionally driven eddies, considerable masses of coastal water are carried offshore near the surface. When this takes place the compensation may occur at some quite distant part of the continental shelf. In all probability an equivalent volume of more saline water must move inshore along the bottom. It seems possible that such major disarrangements of the coastal circulation can have important biological consequences, especially during the spawning season. If the causes for such rather sudden breakdowns in the normal pattern of coastal circulation were more clearly understood, it might be possible for fisheries-investigators to predict the future catch without having to sample year after year the new additions to the population. Physical oceanographers have rather avoided inquiring into the causes of ocean-currents. They have been content merely to note that for several reasons they do flow. In the case of coastal currents, however, a better understanding of the factors which from time to time disturb them might open up many new lines of investigation. It is partly for this reason that it is being urged that more effort be made to perfect an observational procedure which has a chance of uncovering causes. The techniques now in general use seem largely to overlook this possibility.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

FLOOR OF THE NORTH PACIFIC OCEAN

F. Betz, Jr., and H. H. Hess

During the last few years, ships of the United States Navy have taken a huge number of sonic soundings on lines crossing the North Pacific Ocean. As a result of these it was possible for the Hydrographic Office to publish a new bathymetric chart of this area last year, which was a great improvement over previously existing bathymetric charts.

Using the same data as employed by the Hydrographic Office, the writers recontoured the area with the special purpose of locating and delineating structural trends on the floor of the North Pacific.

Pronounced lineal trends were found in the area between the Marianne arc and the coast of North America. These may possibly be fracture-zones. The most pronounced trends strike approximately north 80° east and extend from the Marianne arc almost all the way across the ocean. Less pronounced cross-trends of north 55° west, north 70° west, and north 45° west are to be noted in the central Pacific. The Hawaiian Island group lie along a line 2,400 miles long striking north 65° west. This strike does not itself appear to be a line of fracturing having this direction but rather a series of short north 55° west, north 70° west, and north 60° east trends grouped along what might be termed the "Hawaiian Swell." The Swell itself is some 600 miles wide. Its great width suggests that it cannot be accounted for solely by the amounts of volcanic material which have been extruded from its present volcanoes and probably much more numerous volcanoes of the past, but is rather a structural upwarp along the crest of which volcanism has been active. There is a suggestion of the possibility that the Hawaiian volcanoes lie on the intersections of northeast and northwest fracture-lines.

It is hoped that the charts can eventually be published so that they can be studied by any one interested in the problems presented.

Princeton University,
Princeton, New Jersey

PRELIMINARY RESULTS OF MEASUREMENTS OF TEMPERATURE- AND SALINITY-VARIATIONS IN THE GULF STREAM: MARCH 1940

H. R. Seiwell

(Contribution No. 263 of the Woods Hole Oceanographic Institution)

Repeated measurements of temperature and salinity over extended periods from anchored vessels have shown that significant short-period variations of oceanographic properties occur at fixed points in the ocean-space. The phenomenon, observed to great depths in the ocean-basins, arises because of internal vertical and lateral motions of the water-layers; in regions of not too strongly sloping isohaline and isothermal surfaces (as the western Sargasso Sea), vertical displacements dominate, whereas elsewhere (as the Gulf Stream) both lateral and horizontal displacements may be effective. Large diurnal temperature-variations have been recorded in the western Atlantic, where for considerable distances in all directions isothermal surfaces are only slightly sloping, and, as a result of scattered investigations, it is to be inferred that the phenomenon is of general occurrence and that somewhat corresponding results could be observed in all oceans. Thus, during 14 days of continuous observations at Atlantis station 3091 (about 110 miles northwest of Bermuda), 24 hourly temperature-ranges up to 2°.50 were observed at depths of 800 meters, up to 1°.45 at 1,000 meters, and up to 0°.31 at 1,300 meters.

In oceanic regions of strongly sloping isothermal and isohaline surfaces where lateral, as well as vertical displacements, may be of equal significance, even greater diurnal temperature-variations occur at fixed depths. Thus, at Atlantis anchor station 3777 (28° 55' north, 79° 36' west), located in the axis of the Gulf Stream off Cape Canaveral, a maximum diurnal temperature-range of 3°.38 at 250 meters and a salinity range of 0.57 ‰ at 350 meters were recorded during 48 hours of continuous measurement ($04^h\ 52^m$ February 12 to $04^h\ 16^m$ February 14, 1940, GCT). Diurnal inequalities in amount of disturbance are brought out by comparison of 24 hourly temperature-ranges (Table 1). During the first period (maximum temperature-range 3°.38), temperature-ranges at three depths were in excess of 2°, at four depths in excess of 1°.5, and at ten depths in excess of 1°.0, whereas during the second (maximum range 2°.15) the range at only one depth was in excess of 2°, at three depths in excess of 1°.5, and at 11 depths in excess of 1°.0.

Since anchor station 3777 was located in that part of the Gulf Stream where isothermal and isohaline surfaces were most tilted, and since its position, determined on the basis of a hydrographic section across the current, closely coincided with that of hydrographic station 3773 (29° 00' north, 79° 37' west), horizontal gradients in its immediate vicinity may be estimated from observations at adjacent hydrographic stations 3772 (28° 58' north, 79° 29' west) and 3774 (29° 00' north, 79° 45' west) [distance between stations 3772 and 3773 = 19.49 km and between 3773 and 3774 = 12.99 km]. Temperature-gradients both east and west of 3773, in general, increased downward from the surface; to the east (3772 - 3773), average horizontal temperature-

Table 1--Summary of temperature- and salinity-variations at fixed depths, Atlantis anchor station No. 3777 (28° 55' north, 79° 36' west)

[Minimum and maximum temperatures and salinities and total ranges for entire 48-hour observation period (04^h 52^m February 12 to 04^h 16^m February 14, 1940, GCT), first-day temperature-range for observations during first 24-hour period, second-day temperature-range for second 24-hour period; salinity-estimations made on alternate samplings]

Depth	Temperature					Salinity		
	Minimum	Maximum	Total range	24-hour range		Minimum	Maximum	Total range
				1st day	2nd day			
	°	°	°	°	°	°/oo	°/oo	°/oo
0	23.0	24.1	1.1	0.3	1.1	36.19	36.34	0.15
50	22.90	23.65	0.75	0.30	0.71	36.14	36.42	0.28
100	22.50	23.60	1.10	0.39	1.10	36.16	36.60	0.44
150	21.13	23.54	2.41	2.41	1.34	36.22	36.64	0.42
200	19.89	22.04	2.15	1.99	2.15	36.25	36.76	0.51
250	16.60	19.98	3.38	3.38	1.52	36.20	36.62	0.42
300	14.70	17.11	2.41	2.25	1.11	35.92	36.31	0.39
350	13.08	15.16	2.08	1.32	1.06	35.66	36.23	0.57
400	11.50	13.82	2.32	1.13	1.32	35.45	35.78	0.33
450	10.15	11.71	1.56	1.05	0.60	35.26	35.47	0.21
500	8.95	10.45	1.50	1.19	0.90	35.02	35.30	0.28
550	8.00	9.56	1.56	1.37	1.54	34.97	35.21	0.24
600	6.80	8.28	1.48	1.25	1.11	34.89	35.00	0.11
650	6.65	7.80	1.15	0.60	1.01	34.87	34.94	0.07
700	6.61	7.61	1.00	0.19	1.00	34.87	35.02	0.15
750	6.65	7.26	0.61	0.24	0.61	34.96	35.06	0.10

gradients increased from 5.131×10^{-8} degrees per cm at the surface to 207.275×10^{-8} at 550 meters, with a secondary maximum of 129.290×10^{-8} at 150-meter depth; and, to the west (2773 - 2774), average horizontal gradients changed from 76.988×10^{-8} at the surface to 359.535×10^{-8} at 350-meter depth, with a secondary maximum of 173.223×10^{-8} at 100 meters. Horizontal temperature-gradients west of station 3773 were, on the average, three times as great as those to the east.

Vertical temperature-gradients at station 3773 were, for equivalent depths, between 83.9×10^3 (at 550 meters) and 4.41×10^3 (at 100 meters) times greater than horizontal gradients to the east (3772 - 3773); eliminating these two extreme values, the ratio of vertical to horizontal gradients to the east $[(\Delta T°/\Delta Z)/(\Delta T°/\Delta D)]$ lay between 2.12×10^2 and 7.65×10^2 with an average value for the water column of 7.315×10^2. On the other hand, vertical gradients at station 3773 were between 29.2×10^2 and 8.58×10^2 times greater than those to the west, and eliminating the three lowest values (at 25, 50, and 350 meters), the ratios $[(\Delta T°/\Delta Z)/(\Delta T°/\Delta D)]$ lay between 1.11×10^2 and 8.58×10^2; the average for the water-column being 2.363×10^2.

Trends of horizontal salinity-gradients in the vicinity of station 3773 were similar to temperature; eastward (3772 - 3773), in general, they increased from 0.513×10^{-8} at the surface to 27.705×10^{-8} °/oo per cm at 550 meters; and westward (3773 - 3774), from 6.929×10^{-8} at the surface to 45.423×10^{-8} °/oo per cm at 350 meters. The average of all horizontal gradients to the west of station 3773 was in excess of three times the average of those to the east. Ratios of vertical to horizontal salinity-gradients $[(\Delta S/\Delta Z)/(\Delta S/\Delta D)]$ averaged 6.50×10^2 to the east and 2.49×10^2 to the west.

Thus, lateral cross-stream displacements of the water-layers of a magnitude between 100 and 1,000 times that of vertical displacements are required to produce the observed diurnal variations of temperature and salinity at station 3777. Since a concept of large-scale lateral swingings of the water-layers is not in contradiction to modern hydrodynamical theory, it seems likely that the observed variations of temperature and salinity at fixed points are a combination of both internal vertical and lateral motions on the water-layers, although their relative effects cannot be separated on the basis of existing information. However, in order to approximate the amounts of vertical and lateral displacements needed to produce the observed diurnal variations, the situation was first examined with respect to the amount of vertical displacements alone. The procedure was carried out by computing assumed vertical displacements of selected isotherms during 24-hour periods, and during the first period vertical displacements ranging from 35 meters for the 12° isotherm (386-421 meters) to 86 meters for the 7° isotherm (592-678 meters), and

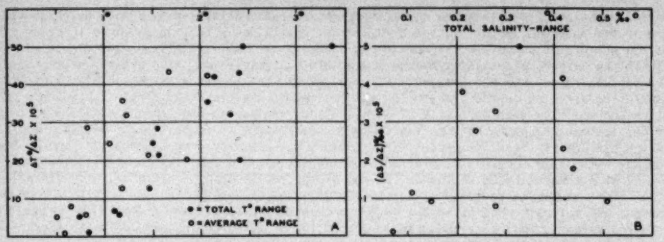

Fig. 1--A = Relationship between total (closed circles) and 24 hourly (open circles) temperature-ranges and vertical variation of temperature ($\Delta T/\Delta Z$); B = Relationship between total salinity-range and vertical variation of salinity ($\Delta S/\Delta Z$), anchor station 3777

during the second period vertical displacements between 16 meters for the 12° isotherm (422-438 meters) and 162 meters for the 7°25 isotherm (584-746 meters) would be required. Reference to Table 1 shows that 24 hourly temperature-ranges were about double at the mean depth of the 12° isotherm where vertical temperature-stratification of the water-column was approximately six times that at the depth of the 7° isotherm. On the other hand, horizontal temperature-gradients at the mean depth of the 7° isotherm were approximately twice as great as at 12°, indicating that lateral displacements would be approximately two times as effective as vertical displacements.

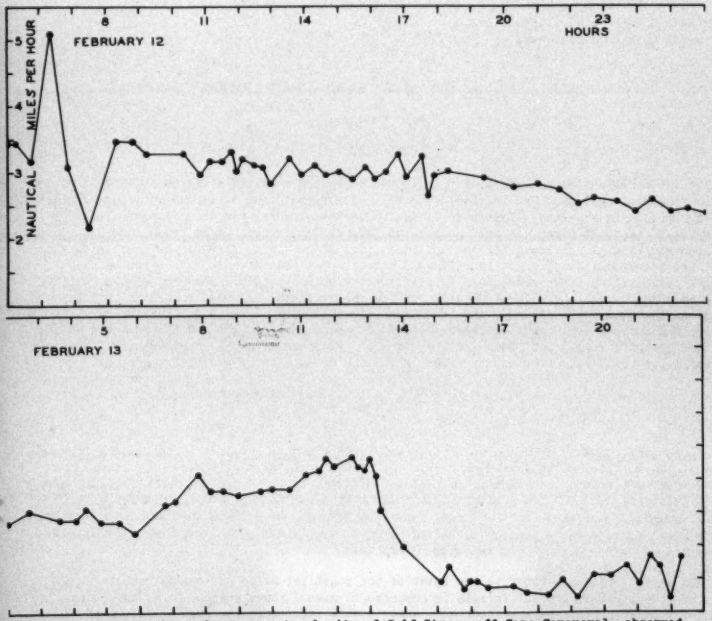

Fig. 2--Variation in surface-current velocity of Gulf Stream off Cape Canaveral, observed $10^h\ 00^m$ GCT, February 12, 1940, to $03^h\ 30^m$, February 14, 1940, anchor station 3777

General relationships between 24 hourly temperature- and salinity-ranges and the physical structure of the water-column at station 3777 are not unlike the situation as found in other regions of the western Atlantic. Total and average temperature- and salinity-ranges (Table 1), particularly the former, closely follow their own vertical gradients, being greater at depths where the vertical gradients are greatest (Fig. 1). Thus, the larger average variations of 2°46 and 0.44 °/oo occurred at depths between 150 and 400 meters where average vertical gradients of temperature and salinity were $(\Delta T/\Delta Z) = 37.38 \times 10^{-5}$ degrees per cm and $(\Delta S/\Delta Z) = 4.01 \times 10^{-5}$ °/oo per cm, as compared with the lesser average ranges of 1°38 and 0.18 °/oo between 450 and 700 meters where average vertical gradients of temperature and salinity were 15.82×10^{-5} and 2.00×10^{-5}. On the other hand, horizontal gradients of temperature and salinity on either side of station 3777 were lower between depths of 150 and 400 meters [$(\Delta T/\Delta D) = 119.62 \times 10^{-8}$, $(\Delta S/\Delta D) = 18.55 \times 10^{-8}$] and higher in the deeper water [$(\Delta T/\Delta D) = 158.02 \times 10^{-8}$, $(\Delta S/\Delta D) = 22.75 \times 10^{-8}$ between 450 and 550 meters]. The situation suggests that over a large part of the water-column at station 3777 time-variations of oceanographic properties at fixed depths are dominated more by vertical than by lateral displacements of the water-layers.

That significant lateral displacements may affect the uppermost layers of the Gulf Stream is suggested by time-variations of surface current-velocity of between 5.1 and 1.2 nautical miles per hour, observed during a 41-hour period at anchor station 3777 (during light southerly winds, 0-2), with a small taffrail log, read at approximate 15-minute intervals (Fig. 2). Surface velocity-gradients as computed for the Gulf Stream section clearly illustrate possible effects of lateral motions of the surface-layer on velocity-variations at fixed points. Thus, maximum surface-velocities at 188 cm per sec midway between stations 3773 and 3774 decreased easterly to 15 cm per sec between stations 3771 and 3772 (39,780 meters) and westerly to 63 cm per sec between 3774 and 3775 (18,670 meters). The average surface-velocity over the 41-hour observation period at anchor station 3777 was 134 cm per sec, nearly agreeing with the computed surface-velocity of 145 cm per sec at hydrographic station 3773.

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THE MUNCH-PETERSON FORMULA FOR THE SO-CALLED "COASTAL TRANSPORTATION FORCE"

Paul Nemenyi

(Abstract)

Of the many factors transforming the beaches under the conditions prevailing on all Danish coasts, the most important are erosion by waves and transportation of eroded material by coastal wave-currents. In technical literature, waves and wave-currents have usually been treated separately. About 35 years ago three Danish engineers, Paul-Vedel, Palle Bruun, and John Munch-Petersen, working on difficult harbor- and beach-protection works, came to the conclusion that these two phenomena--being only two different effects of a common cause, the ocean-waves impinging obliquely upon the coast--can be best treated when combined. They argued that neither the erosion by waves with a crest parallel to the shore-line nor a coastal current in itself could cause considerable changes, and that their combined work, like "a combination of an excavator and a conveyor," leads to the depletion of one coastal section and the building up of another. After a long joint study and a process of trial and error, J. Munch-Petersen proposed a formula for the "coastal transport force" which may be written in the following form

$$C \int_0^{2\pi} h s^2 \sqrt{f} \cos \varphi \, d\varphi$$

where h is the frequency of the wind between the angle φ and $(\varphi + d\varphi)$, s is the quadratic mean value of the velocity of this wind, and f is the "fetch" for the same angle. [In actual computing work, integration can usually be replaced by summation for which J. Munch-Petersen gave a simple graphical method. The quadratic mean values of s can be replaced by arithmetic mean values times 1.12, as shown by the author (see reference below).] Most important distinguishing feature of this formula is that it takes into account the "fetch", and that, accordingly, it eliminates all winds coming from the side of the land.

All aerological data refer to the point of the coast for which the coastal sand-transport is to be investigated, and the formula is supposed to give a rough indication of the intensity of material-transport to be expected, and, what is more important, its sign (plus or minus) should indicate whether the drift of material is to be expected on the average in the direction of the positive coordinate axis or in the opposite direction.

Although the formula does not contain many of the important factors, and is not based upon exact theoretical considerations, it has shown in the light of data collected on sandy beaches of fairly similar granular composition to give reasonably good comparative values and in any case to give the correct direction of the average drift as known from direct observations and measurements of the shore-processes. This has been proved through extensive computations of Professor Munch-Petersen. In the year 1935-36 the present writer improved, at Professor Munch-Petersen's suggestion, upon the methods of computation, and with the improved methods made extensive computations concerning Danish coasts as well as a few points along the coasts of other Baltic countries with favorable results. [See J. Munch-Petersen, "Uber Materialwanderung an Küsten des Baltischen Meeres" and Paul Nemenyi "Bemerkungen Zur Ermittlung Der Materialführenden Kraftkomponents," both of which were published in the Proceedings of the Fifth Hydrological Conference of the Baltic States, Helsinki, 1936; for literature previous to these papers, see the bibliography in J. Munch-Petersen's publication.] Finally, P. Revelis, engineer of Letlands Hydraulic Structures Board (Riga), has recently made a special study of the formula using data from coasts of his country, and he too found satisfactory agreement between prediction and actual shore changes [see Sv. Svendsen, "Munch-Petersens Formel for Materialvandring," Stads-og Havneingeniören, December 1938].

It would be relatively easy to improve upon the formula, among other things by elimination of all winds too weak to move any materials. Such a "sifting out" of the winds would, however, increase substantially the computational work required. Also, more fundamental improvements might be contemplated.

In the present simple form, however, the Munch-Petersen formula is a particularly convenient tool for a comparatively rapid and simple orientation. It would therefore be of value for empirical hydrology if the American Beach Erosion Board would compare some of its extensive data with results obtained by using Munch-Petersen's formula for American beaches. With the help of the great rectangular laboratory-basins available in the United States, the Munch-Petersen formula could also be studied under conditions in the laboratory; the waves in this case of course should not be produced by the so-called "wave-machine", but by a row of fans, preferably in connection with devices warranting a uniformly turbulent wind.

The author of this paper is indebted to the trustees of the Rask Örsted Foundation for making possible his shore-process studies. He also remembers gratefully the late Professor J. Munch-Petersen (deceased at the beginning of 1939) whose unusual wealth of experience concerning coastal phenomena was a great help and inspiration to the author in his studies.

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF VOLCANOLOGY

REPORTS AND PAPERS

Washington, D.C.
April 24, 1940

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REPORTS AND PAPERS

CRATER LAKE AND THE CALDERA PROBLEM

Howel Williams

No manuscript or abstract of this paper was submitted.

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VELOCITY OF BASALTIC FLOWS INDICATED BY LAVA-TREES

Robert L. Nichols

(Abstract)

Many data on the velocity of lava-flows have been obtained from the Hawaiian Islands, Vesuvius, Etna, and other areas of present-day volcanic activity. Although velocities ranging from a fraction of a mile to a few miles per hour are usual, reports have been made of velocities as high as 40 miles per hour.

To determine the velocities of prehistoric flows, two methods can be used. The first method involves the use of the Jeffreys formula. This formula is for laminar flow and in cgs units is

$$V = g \sin A \, d^2 p / 3u$$

where V is mean velocity with regard to depth, g is acceleration of gravity, A is angle of inclination, d is depth, u is the ordinary coefficient of viscosity, and p is specific gravity. If the depth, gradient, and specific gravity of a prehistoric lava-flow can be obtained, a reasonable viscosity can be assumed and its approximate velocity calculated.

The second method is based upon an analysis of lava-trees. Lava-trees are common features on flows which have invaded forests and surrounded trees. One type consists of a thin sheath of lava which solidified around the tree and which projects above the surface of the flow. The sheath increases in thickness from top to bottom, and it is higher on the upstream than on the downstream side of the flow.

The shape of a lava-tree is a function of the viscosity and velocity of the flow. If the shape of a lava-tree is known, a reasonable viscosity can be assumed, and the approximate velocity of the flow at that point can be calculated.

The lava-tree method can be applied only to flows which are practically uneroded, as lava-trees are fragile and are therefore quickly destroyed. The Jeffreys-formula method, however, can be used on flows which are greatly eroded as well as on those on which there are no lava-trees.

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A LAVA-FAN NEAR BEND, OREGON

Robert L. Nichols

(Abstract)

Lava Butte, a 500-foot cinder cone near Bend, Oregon, is almost completely surrounded by fresh, barren, and uneroded basaltic flows. By far the most conspicuous of these is the aa flow which broke out from the south side of the butte Near the source of this flow there is exposed, with unusual completeness, a lava-fan.

The fan is approximately 2,200 feet long, 1,100 feet wide, and 250 feet thick. Both in plan and in section it is shaped like an alluvial fan or cone. One of its most striking features is its asymmetry. The west side is short and steep, the east side is long and flat. This asymmetry is due to the westward slope of the area at the time of extrusion. The south, southeast, and east sides of the fan are made up of more than 30 superimposed flows, many of which have

surface-expression. They vary in thickness from less than five to more than 17 feet, and the largest cover only a few tens of acres. Because the successive flows became progressively smaller, the ends of most of them are not buried. From the east they look like a series of terraces. Because the older flows are as fresh and youthful-looking as the younger, the time-interval between them must have been short. The west side of the fan is undoubtedly also made up of many individual flows, but the last flow to be extruded there was so extensive as to bury the earlier ones.

A main channel and three distributary channels are found on the fan. All are close to Lava Butte; the main channel originates there, and the other three branch off from the main channel at distances of 200 to 300 feet from it. All four have been more or less modified by landsliding, collapse, and slump, so that considerable quantities of talus and landslide blocks have accumulated on their floors. In general, they are deepest near their sources and shallowest near their termini. Five facts indicate that these channels are the open channels characteristic of aa-flows and not the collapsed tunnels of pahoehoe lava. First, most of the lava on the fan is aa. Second, their cross-sections are typical of channels but not of collapsed tubes. Third, collapsed roofs are not found on the bottoms. Fourth, they are bordered by the levees which are so characteristic of aa channels. And fifth, superimposed drip-surfaces in places completely veneer the walls of the channels. These drip-surfaces are continuous with the small flows of which the levees are built.

These channels represent, therefore, the former positions of liquid lava-streams. It was from these streams that the lava which built the fan was derived. Drainage of these streams resulted in the formation of the channels. The height of the lava-levees which border the main channel and the general shape of the fan indicate that the position of the main lava-stream was more or less permanent during the growth of the fan.

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CRYSTALLIZATION OF PYROXENES AND THE PIGEONITE PROBLEM

H. H. Hess

(Abstract)

An abstract contaihing only conclusions from a study of pyroxenes will be presented at this time. A complete treatment of the subject will be prepared for publication in the near future.

Conclusions--(1) Under natural conditions, limited rather than complete solid solution is found in the clinopyroxene field between diopside-hedenbergite pyroxenes and clinoenstatite-clinoferrosilite pyroxenes.

(2) Two clinopyroxene phases in this series may crystallize simultaneously in equilibrium with each other in a large portion of the total field.

(3) Two varieties of pigeonitic pyroxene are recognized: (1) One which will be called pigeonite is a member of the clinoenstatite-clinoferrosilite series with a small amount of dissolved diopside-hedenbergite (Wo--nine per cent molecular); (2) another which will temporarily be called augite-pigeonite is a member of the diopside-hedenbergite series (Wo--25 per cent to 40 per cent) with a considerable amount of dissolved clinoenstatic-clinoferrosilite. The latter is equivalent to most augites and diallages of igneous rocks.

(4) The pyroxenic phases of the groundmass of volcanics do not appear to differ in any way in composition from the pyroxenic phases present in the slowly cooled intrusives, so that the concept of complete solid solution of the pyroxenic phases in the groundmass of volcanics in contrast to limited mutual solubility in intrusives is unwarranted.

(a) It is commonly reported that the groundmass pyroxene of volcanics is a "pigeonite" with highly variable properties so that optic angles ranging from 2V = 48° to 2V = 0° in the same thin section are described in many cases. Such careful observers as Kuno, for example, note two pigeonites in many volcanic rocks. The writer's observations indicate that the presence of two pigeonitic clinopyroxenes is the rule rather than the exception, one with an optic angle of 45° ± 4° and the other with an optic angle of 0° ± 20°.

(b) The two pyroxenes mentioned above are identical in chemical composition with the "augite" and "hypersthene" of equivalent plutonic igneous rocks although the optical properties of the

latter pair are very different from the former pair as a result of exsolution of En-Fs from the Di-Hed pyroxenes and Di-Hed from the En-Fs pyroxenes.

(5) Pigeonite, as defined above, on slow cooling inverts to an orthopyroxene with coarse exsolution lamellae of Di-Hed parallel to a pyramidal plane (commonly [112]). The orthopyroxene thus formed may later, with further slow cooling exsolve the rest of its dissolved Di-Hed as fine lamellae parallel to 100 as do normal orthopyroxenes of slowly cooled intrusives.

(6) Augite-pigeonite, as defined above, exsolves En-Fs with slow cooling and the exsolved material appears as fine lamellae parallel to 100, 001, or both. Such pyroxenes are normally described as "diallages."

(7) The pyroxenes may be used effectively as geological thermometers.

(a) Based on the inversion of pigeonite, as defined above, to orthopyroxene, the Stillwater and Bushveld Igneous Complexes started crystallization at approximately 1135°C. [Temperatures estimated from inversion-curves of clinoenstatite-clinoferrosilite series to orthopyroxene as given by Bowen and Schairer.] After about 60 per cent of the magma had crystallized the temperature had decreased to 1120°C, the final consolidation temperature of the Skaergaard intrusion (after 98 per cent had crystallized) was approximately 950°C, based on Wager's and Deer's interpretation that the Hedenbergite present in some of tnose rocks has inverted from a b-Wollastonite solid solution. This suggests that the total range of temperature during crystallization of a basaltic magma of the Stillwater-Bushveld-Skaergaard type was accomplished in 185°C (from 1135°C to 950°C).

(b) The clinopyroxenes in peridotites derived from what the writer considers to be an ultramafic magma have very little dissolved En-Fs which is consistent with the writer's previous conclusion that this type of magma has a very low temperature. The clinopyroxenes from peridotites derived by crystallization differentiation from a basaltic magma have a high content of dissolved En-Fs.

(c) Clinopyroxene skarn rocks and clinopyroxenes deposited from hydrothermal solutions commonly contain very little dissolved En-Fs and can tnus be distinguished from magmatic pyroxenes.

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SILICIFICATION AND LOCAL GRANITIZATION IN THE READING HILLS

Donald M. Fraser

(Abstract)

Quartz and microcline replacing minerals in pre-Cambrian and Cambrian formations in the Reading Hills indicate a magmatic source for solutions that have introduced large volumes of material. This introduction was likely in post-Hardyston time.

Introduction--The widespread occurrence of quartz showing cross-cutting and replacement relationships to the other minerals of pre-Cambrian formations of the Reading Hills, in eastern Pennsylvania, invites a study of tne source of the silica involved.

Also quartz and microcline found in places replacing the matrix of the Hardyston sandstone and forming additions to the original sedimentary grains of quartz and feldspar must be explained.

The formations involved are the Pochuck diorite-gneiss, the Byram granite-gneiss, and the Hardyston sandstone. The first two are more or less metamorphosed pre-Cambrian igneous masses and the latter the lowest Cambrian in the area. Other pre-Cambrian formations have likewise suffered the introduction of silica but they are of small areal extent and are not described here.

Description of specimens--The Byram gneiss, which in many places is a massive granitic rock lacking conspicuous streaking or banding, has invaded the older Pochuck gneiss and has assimilated large quantities of the latter. The resultant product has crystallized to form a granitic rock of intermediate composition. The mineral assemblage most commonly encountered is oligoclase or andesine, microcline, perthite, quartz, and hornblend and biotite in variable percentages. Pyroxene occurs less frequently. In places the Byram granite-gneiss retains remnants of only slightly altered dioritic material from the Pochuck, while in other places assimilation of the older material is complete.

Fig. 1--Area of quartz replacing sericitized oligoclase [Squarish grain of strong relief in center is zircon; small area of microcline is seen at left center of view]

Fig. 2--Quartz replacing oligoclase [Inclusions in quartz show small zircon grain at lower left and apatite grain with an oligoclase remnant just above center of view; the dark streak extending from altered oligoclase is a strain-shadow; dark altered area along edge of oligoclase approximates saussurite in composition]

Fig. 3--Large quartz grain nearly at extinction showing numerous inclusions of feldspar derived from replacement of feldspar grains

Fig. 4--Oligoclase grain showing encroachments of quartz at top and bottom of grain

Fig. 5--Larger quartz area, showing strain-shadows, is replacing oligoclase-feldspar for the most part [The plagioclase grain in lower part of field shows the twinning bands have been truncated by the replacing quartz]

Fig. 6--Two larger quartz grains replacing finer-grained feldspars and leaving a narrow zone of smaller feldspar grains between the two areas

Fig. 7--Granitized Hardyston arkosic quartzite in plane light showing welding together of adjacent grains by additions formed around feldspars [Area having finer texture at lower right shows original arkosic sediment]

Fig. 8--Same field as Figure 7 showing extended growth of microcline around original feldspar

In all of the various gradations which have resulted from the invasion of the Byram granite one finds evidence of a still later introduction of silica. This material occurs as quartz grains usually larger than the original quartz in the rock and shows cross-cutting and replacement-relationships to the earlier minerals (Figs. 1 and 4). Some of the later quartz has been introduced in a manner that has resulted in a bleb-like formation of quartz masses in the earlier rock. Other areas show larger irregular quartz grains partially replacing several feldspar grains (Figs. 5 and 6), and in places also replacing the other minerals of the primary mineral assembly. In some areas the replacement has gone so far that only remnants of the original feldspar material are now found in larger quartz grains (Fig. 3). Where zircon and apatite grains have been encountered they are usually not replaced but have been retained as inclusions in the later quartz (Fig. 2). In general, the minerals suffering the most attack are the plagioclase feldspars. However, in some sections hornblend has been replaced in part by the later quartz. The plagioclase grains commonly show partial sericitization or saussuritization.

Associated with the quartz replacement are much smaller amounts of microcline (Fig. 1). This material is often found replacing the plagioclase and due to its association with the cross-cutting quartz is thought to represent microcline material carried by the solutions which introduced the quartz. In the case of granitic rocks in which microcline is a primary constituent it is unsafe to ascribe a great deal of the material of this composition to introduction but it appears that smaller amounts are surely of later origin than the primary crystallization.

Thin sections of Hardyston sandstone from a district south of Bethlehem show abundant extended growth-areas around both quartz and feldspar grains (Figs. 7 and 8), and sections of the Hardyston from other localities show similar relationships. The original material is a sediment of arkosic character in which the grains are made up of quartz, perthite, and microcline. Considerable sericite and rather abundant apatite are found in the inter-grained areas. The zones of extended growth around the quartz grains show only occasional development of crystal outlines, but the areas of additive material have the same optical orientation as the grains they surround. The additions of microcline to the feldspar grains, however, have in many cases developed crystalline outlines which in the thin sections are rhombic or rectangular in shape. The resulting rock is therefore somewhat coarser grained than the original sandstone and shows the close interlocking of the grains that is to be expected in a granitized material.

Interpretation--The presence of abundant introduced silica in the crystalline rocks together with the strong suggestion of introduced microcline in these rocks as well indicates an invation of aqueo-igneous material into the area at some time following the primary crystallization of these rocks. The finding of both quartz and microcline additive material in the Hardyston formation suggests the presence of an igneous source for these materials in the general district in post-Hardyston time. The previous finding of small amounts of pegmatitic material [D. M. Fraser, Paleozoic pegmatites in the Pennsylvania Highlands, Amer. Mineralogist, v. 21, No. 10, pp. 662-666, October 1936] has indicated such an occurrence. With the recognition now of a rather large volume of introduced silica and possibly also of microcline, it is suggested that igneous masses had sufficient proximity to the district to cause the permeation of the entire area by a large amount of their end-stage silica-rich aqueous emanations. It is to be noted that the sections that show introduced silica are not infrequent among the sections of rocks from the district. Most of the sections examined show the presence of introduced quartz in amounts which would surely average over five per cent of the volume of the rocks studied.

Circulating meteoric waters may, of course, be suggested as the origin of the material under consideration. It is true that large volumes of jasper or jasperoid occurring in the district might be accounted for by such solutions. Such deposits are often porous and show encrustation structures. They do not give evidence of having been formed under confining stress and indicate that there was ample room for the growth of the material being laid down. In distinction to this the quartz and feldspar found in the crystalline rocks and as additions to grains in the Hardyston have apparently been laid down under conditions of fixed volume. They do not merely fill openings but replace earlier materials; the primary (or metamorphic) minerals of the crystalline rocks and the aggregate grains (apatite excepted) making up the matrix of the Hardyston. In addition, it is more reasonable to expect solutions which carry both quartz and feldspar to have an origin more closely magmatic than meteoric. In so far as the replacement of the pre-Cambrian rocks are concerned, the action could have been brought about by solutions associated with the later stages of the Byram invasion. However, the similar occurrence of quartz and microcline in the pre-Cambrian and the Hardyston formations suggests the introduction of these materials in both of these age-groups at the same time.

The invading solutions altered the pre-Cambrian rocks chiefly by replacement while the introduction of quartz and microcline into the Hardyston has resulted in local granitization.

The solutions probably formed some at least of the numerous quartz veins found in the overlying Cambro-Ordovician limestones and may also have deposited smaller amounts of feldspar in these higher formations which may be recognized when they are studied microscopically.

It is typical for the introduced quartz to show strain-shadows, and it is therefore supposed that movement at a time later than the replacement of the original minerals has deformed the rock. In some of the more highly sheared specimens it is difficult to interpret the proportional amounts of primary and introduced quartz. The presence of structures that indicate deformation following the deposition of the quartz does not, however, fix the age of introduction with any certainty. The movement might have been in pre-Cambrian time in so far as the pre-Cambrian formations are concerned or could have equally well occurred at the time of Appalachian orogeny.

Conclusions--We may conclude that large amounts of silica and smaller amounts of microcline have been introduced in the pre-Cambrian crystalline rocks and in the Hardyston sandstone.

Previous recognition of pegmatitic material in the area has indicated the presence of magmatic solutions in post-Hardyston time. The interpretation now of at least five per cent of the volume of the pre-Cambrian rocks to be of introduction and replacement-origin points to a great volume transfer of quartz and microcline which is to be measured in terms of cubic miles of materials. The solutions responsible were surely of magmatic origin and probably were post-Hardyston in age but some of the changes in the gneisses may have occurred in pre-Cambrian time.

Lehigh University,
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GENESIS OF THE BLACK RANGE TIN-DEPOSITS, NEW MEXICO

Carl Fries, Jr.

(Abstract)

Cassiterite-bearing veinlets in Tertiary rhyolite flows are exposed at more than a dozen places in a district that covers approximately 450 square miles in southeastern Catron County and northwestern Sierra County, New Mexico. Most of the veinlets are in zones of altered and sheared rhyolite adjacent to belts of vertical flow-layering that appear to be the sites of composite fissure vents; a few are in underlying pyroclastic beds. The veinlets are irregular and discontinuous, and range in size from thin films which are only faintly visible and extend only one or two feet to tabular bodies more than an inch thick and 20 to 30 feet long.

Similarity of mineral assemblage and sequence of deposition in the veins and in the fresh and altered rhyolite suggests that the deposits were formed during the period of cooling of the flows. Vesicles of the fresh rhyolite contain topaz, garnet, magnetite, specularite, tridymite, chalcedony, opal, quartz, fluorite, zeolites, and perhaps cristobalite. The altered rhyolite contains all of these except topaz and garnet, and contains cassiterite close to veinlets. In the veinlets, the silica minerals and zeolites were deposited later than cassiterite, and the specularite, which is abundant, formed earlier.

The mineralizing fluids came in part from the cooling flows and in part from the deeper rhyolite magma. The fluids from the magma rose through fissures formed by movement along the vents shortly after solidification of the flows. Localization of some deposits may have been governed by fractures due to contraction.

The tin-deposits are of the type termed by Buddington xenothermal, formed at high temperature and under low pressure.

U. S. Geological Survey,
Washington, D. C.

WATER WITH SOME ALKALI SILICATE SYSTEMS UP TO 3,000 POUNDS PRESSURE

George W. Morey and Earl Ingerson

(Abstract)

The apparatus for studying the phase equilibrium-relationships in systems containing water and silicate [previously described, Amer. J. Sci., v. 35A, p. 217, 1938] has been modified for

more convenient operation and higher pressures. In this apparatus, the silicate mixtures are heated under a constant pressure of water-vapor, the charge is quickly cooled by quenching, and is examined. By changing the temperature at constant pressure, the melting point at that pressure can be determined; repetition at a series of pressures and analysis of the quenched charges enable the P-T-X relationships to be established.

The results presented referred chiefly to the 3,000-pound isobar in the systems Na_2SiO_3--SiO_2 and Na_2O--CaO--SiO_2. In the system Na_2SiO_3--SiO_2, this isobar is approximately parallel to the melting-point curve for the anhydrous system, with a lowering of approximately 175° at Na_2SiO_3, of 165° at $Na_2Si_2O_5$, and the eutectic $Na_2Si_2O_5$--SiO_2 apparently is displaced slightly to a higher SiO_2-content.

In the system Na_2O--CaO--SiO_2, the region studied was the field of devitrite, $Na_2O \cdot 3CaO \cdot 6SiO_2$ and adjoining portions of the fields of $Na_2O \cdot 2CaO \cdot 3SiO_2$, $Na_2O \cdot 2SiO_2$ and quartz. At 3,000 pounds water-pressure the field of devitrite is invaded by that of both quartz and $Na_2O \cdot 2CaO \cdot 3SiO_2$, and consequently is decreased in area. In some instances, the liquidus temperatures at 3,000 pounds are higher than in the anhydrous system. This probably is associated with the change in primary phase.

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PHASE-RELATIONS IN THE SYSTEM TELLURIUM--SILVER

F. C. Kracek and C. J. Ksanda

(Abstract)

The melting-point diagram of the system tellurium--silver may be regarded as composed of two adjoining systems, (1) the system Te-Ag_2Te, and (2) Ag_2Te-Ag. In the first part of the system the liquidus curve first drops from the melting point of Te at 451° C to a eutectic located at 351° C, 33 atomic per cent Ag. From the eutectic the curve then rises toward the melting point of Ag_2Te at 959° C. This portion of the curve consists of two main branches, with Ag_3Te_2 as the primary phase from 351° C to 465° C, and Ag_2Te as the primary phase above that. At 465° C Ag_3Te_2 melts incongruently with the formation of crystals of Ag_2Te, and a liquid of 49 atomic per cent Ag.

In the second part of the system two liquids coexist with crystals of Ag_2Te at 875° C, from 69 to 91 atomic per cent Ag, and there is a eutectic with Ag_2Te and Ag as constituents at 870° C, 92 atomic per cent Ag.

The compound Ag_3Te_2 has two inversions which occur on heating at 286° C and at 425° C.

Ag_2Te has an inversion which occurs on heating at 145° C in the pure compound and in the presence of excess silver. In the presence of excess tellurium this temperature is 132° C.

The mineral hessite yields X-ray diffraction-patterns which are identical with those of synthetic Ag_2Te, both at ordinary temperature and above the inversion.

The mineral empressite, according to the literature, has the composition AgTe. No such compound was found in the system, and a specimen of natural empressite gave a foreign pattern.

A foreign pattern was also obtained from a specimen of stutzite. Nominally the composition of stutzite is Ag_4Te, but actually, synthetic mixtures of such composition gave only a mixed pattern of lines due to Ag_2Te and Ag.

The specimens of hessite, empressite, and stutzite were lent to us by the United States National Museum and the Mineralogical Museum of Yale University, through the courtesy of Dr. W. F. Foshag and the late Professor W. E. Ford.

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THE SYSTEM ALBITE-ANORTHITE-SPHENE

A. T. Prince

(Abstract)

This system has been studied to determine the phase-relationships at the liquidus temperatures under atmospheric pressure. The system is of interest because it deals with the well-known plagioclase series and the common accessory mineral sphene. Its petrological significance is considered where diopside is taken as a fourth component. The compositions of mixtures in a certain part of the tetrahedron so formed, approach those of simple diorite and simple basalt.

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THE SYSTEM ALBITE-WOLLASTONITE-NEPHELINE

Wilfrid R. Foster

(Abstract)

A study has been made of the high-temperature equilibrium-relations, at atmospheric pressure, of the three silicates sodium aluminium polysilicate, calcium metasilicate, and sodium aluminium orthosilicate. These constitute the fundamental molecules of the rock-forming minerals albite, wollastonite, and nepheline, respectively. The system forms a plane in the quaternary system soda-lime-alumina-silica. As a preliminary to the study, two of the limiting systems were investigated, namely, nepheline-wollastonite and albite-wollastonite. The three minerals concerned do not form a true ternary system, there being a plagioclase field instead of one of albite. The minimum-temperature point of the entire system is the albite-nepheline eutectic.

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF HYDROLOGY

REPORTS AND PAPERS

Washington, D.C.

April 25, 26, 27, 1940

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COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1939-40

C. S. Howard, Chairman

The membership of this Committee is as follows: I. A. Dennison, National Bureau of Standards, Washington, D. C.; C. S. Scofield, Bureau of Plant Industry, Department of Agriculture, Washington, D. C.; D. G. Thompson, United States Geological Survey, Washington, D. C.; Prof. T. G. Thompson, University of Washington, Seattle, Washington; and C. S. Howard (Chairman), United States Geological Survey, Washington, D. C.

The Committee arranged for the presentation of the following five papers at the 1940 Spring meeting: (1) Salt-water intrusion in the Connecticut River, by C. S. Howard, United States Geological Survey; (2) Salinity-movement and its causes in the Delaware River Estuary, by William D. Mason and Wallace R. Pietsch, Sun Oil Company; (3) Salinity of lower Savannah River in relation to tidal action and stream-flow, by William L. Lamar, United States Geological Survey; (4) Corrosion of ferrous and nonferrous metals and the behavior of metallic coatings in tidal marsh, by I. A. Dennison, National Bureau of Standards; (5) The contamination of underground waters by salt water near Parlin, New Jersey, by H. C. Barksdale, United States Geological Survey.

In connection with these papers anyone studying the subject of salt-water intrusion will be interested in a few other papers which have appeared during the past years.

A study of salt-water intrusion in the Lake Washington Ship Canal near Seattle, Washington, was started in 1917. A report [see 1 of "References" at end of report] published in 1927 suggests methods of controlling the salinity of a body of fresh water connected with the sea by means of a canal-and-lock system. Analytical results are given to show the concentrations of chloride in Lake Union, Lake Washington, and the Ship Canal.

A report [2] published in 1931 gives the results of a study of salt-water conditions in the lower part of the Sacramento River. The intrusion of salt water under different conditions is described and statements are made concerning the amount of stream-flow necessary to prevent the invasion of salt water. Suggestions are made for the control of salinity through the release of water from storage-reservoirs in the upper part of the basin.

The intrusion of ocean-water in sections of the South Coastal Plain, California, is discussed in a report [3] published in 1933. This report presents data on intrusion of sea-water based on the analyses of samples from 129 wells in the Basin from Santa Monica to Costa Mesa. The statement is made that while there may have been some evidence of sea-water contamination in wells along the beach the contamination had not progressed very far at the time of the study.

The report of the salinity-conditions on the Delaware River given at the 1940 meeting of the Union is based on extensive studies made by the authors and others to determine the effects of diversion of water from the upper part of the Basin for use as a part of the Public Water Supply system of New York City. For complete details of these studies reference should be made to the files of the Delaware River Conservation Association and of the Pennsylvania Department of Health.

Considerable attention has been given to the contamination of ground-waters by sea-water in a number of coastal communities. It is apparent that more consideration of the problem of salt-water contamination will be necessary because of the increasing development of ground-water supplies.

A recent paper discusses the chemical character and industrial utility of ground-waters in the Houston-Galveston Area [4]. In this Area the daily use of ground-water for industrial purposes is over 100,000,000 gallons. Information is given concerning the character and changes in character and the possibility of contamination with salt water through overpumping.

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[1] E. Victor Smith, Salinity of the Lake Washington Ship Canal, Univ. Washington Engineering Experiment Station, Seattle, Washington, Bull. 41, May 1, 1927.

[2] Edward Hyatt, Variation and control of salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay, Div. Water Resources, Dep. Pub. Works, State of California, Bull. 27, 1931.
[3] Edward Hyatt, Quality of irrigation waters, Div. Water Resources, Dep. Pub. Works, State of California, Bull. 40, 1933.
[4] Margaret D. Foster, Ground waters of the Houston-Galveston Area, Indust. Eng. Chem., v. 31, pp. 1028-1034, 1939.

U. S. Geological Survey,
Washington, D. C.

COMMITTEE ON RAINFALL, 1939-40

Merrill Bernard, Chairman

The Research Committee on Rainfall is comprised of the following members: David E. Donley; W. W. Horner; W. G. Hoyt; J. B. Kincer; Carroll F. Merriam; Thorndike Saville; L. K. Sherman; Mary O. Soroka; C. W. Thornthwaite; and Merrill Bernard (Chairman).

The Committee has engaged in such routine activities as the preparation of bibliography on rainfall, participation in the round-table discussion on infiltration, and sponsorship of papers on rainfall at the spring meeting of the Section of Hydrology in Washington in 1939.

In several respects the past year has been outstanding in fields embracing the recording and analysis of precipitation-data. Deficiencies in data-sources coming to attention as the result of flood-control planning are being overcome through cooperative effort of the Departments of War and Agriculture. By June 30, 1940, there will be over 8,000 rain-gages in operation over the country. Table 1 shows the growth of the nation-wide network since its beginning about 1848.

Table 1--Approximate number of rain-gages in operation in the United States, 1848-1940

Year	Number	Year	Number
1848	20	1895	3000
1850	280	1900	3200
1857	440	1910	4000
1862	230	1917	4670
1870	550	1920	4450
1875	680	1930	4900
1880	530	1933	4730
1882	860	1935	5100
1886	680	1939	6700
1890	2250	1940	8100

For purposes of administration the country has been divided into ten hydrologic regions (shown in Fig. 1).

The objectives of the hydrologic program are:

(1) To organize and administer a nation-wide network of precipitation-stations for the purpose of determining the regional regimen of rainfall and to overcome the recognized deficiencies in precipitation-data.
(2) To provide basic data of excessive rainfall during short periods.
(3) To make the fullest use of the facilities of the Weather Bureau, such as its network of climatological and aerological stations, field administrative offices, inspection-services, etc.
(4) To bring all acceptable existing precipitation-stations into the network.
(5) To standardize instrumentation and observational techniques.
(6) To increase the density of precipitation-stations according to a predetermined plan.
(7) To collect, assemble, reproduce, and disseminate all available data for the use of the cooperators in flood-control planning.

When the program was initiated at the beginning of the current fiscal year, the immediate need for data indicated that the work should begin in the central portion of the United States, comprised principally of the area between the Continental Divide and the Appalachian Mountains. Accordingly, the program has been completely organized and is operating in the Ohio River, Missouri River, Upper Mississippi, and Lower Mississippi-West Gulf regions.

In the North Atlantic and Southeast regions, because of the large number of recording and non-recording gages which were already in operation, it was planned to partially organize the hydrologic units and to devote the first year of operation to the integration of existing gages into the network. However, the need for additional recording gages in certain basins became apparent and a limited number have been installed.

Fig. 1--Hydrologic regions of the United States

It was planned originally to identify, with limited personnel, the Southwest, Upper Colorado-Great Basin, North Pacific, and South Pacific regions during this year. There arose, however, an immediate need for data in considerable portions of the Southwest and South Pacific regions, as well as in certain portions of the North Pacific Region. Personnel and equipment have been provided and data are now being gathered in these priority-areas. Plans have been made for completing the program in these regions in the early part of the next fiscal year.

Table 2 shows the status of the program at this time. Rapid progress is being made in establishing stations and the figures given are necessarily approximate. Shown in the Table are the number of recording and non-recording gages (1) in operation at the beginning of this fiscal year, (2) new stations established by the program up to the present time, (3) total number of new stations to be installed by the end of this fiscal year, and (4) the total number of stations to be in operation at the end of this fiscal year.

Table 2--Precipitation-stations of cooperative hydrologic program

Region	Existing at beginning of fiscal year		New stations installed to date		Total number of new stations to be installed by end of fiscal year		Total number of stations to be in operation by end of fiscal year	
	Recording gages	Non-recording gages	Recording gages	Non-recording gages	Recording gages	Non-recording gages	Recording gages	Non-recording gages
North Atlantic	135	660	29	0	40	0	175	660
Southeast	90	525	36	7	40	20	130	545
Ohio River	200	880	100	53	135	75	335	955
Upper Mississippi	70	520	72	22	80	35	150	555
Missouri River	65	760	120	60	200	100	265	860
Lower Mississippi-West Gulf	120	875	105	66	175	125	295	1,000
Southwest	25	375	51	23	55	25	80	400
Upper Colorado-Great Basin	10	200	0	0	0	0	10	200
North Pacific	45	525	8	0	10	0	55	525
South Pacific	50	320	27	0	55	0	105	320
Total	810	5,640	546	231	790	380	1,600	6,020

In addition to establishing new stations as planned, the regional offices are engaged in bringing into the network all existing stations which meet the requirements of the program. It is necessary in many cases to completely rehabilitate the stations in order to bring them up to the established standards.

Rainfall-studies have been conducted by L. K. Sherman for the purpose of determining infiltration-capacities for selected Mid-western basins. Special studies involving rainfall also are being engaged in by R. E. Horton and W. W. Horner. Numerous precipitation-data have been tabulated, and analyzed by the Geological Survey, Soil Conservation Service, and the Forest Service.

Cooperative hydrometeorological studies between the Corps of Engineers, the Department of Agriculture and the Weather Bureau are progressing satisfactorily. Under this plan approximately 1,200 storms of record are being tabulated, mapped, and analyzed.

Investigations in storm-morphology under Dr. C. W. Thornthwaite, Chief, Climatic and Physiographic Division, Soil Conservation Service, are continuing on the Muskingham Basin in Ohio.

U. S. Weather Bureau,
Washington, D. C.

COMMITTEE ON RUNOFF, 1939-40

W. G. Hoyt, Chairman

The Runoff Committee during the year has consisted of H. K. Barrows, Merrill Bernard, E. S. Cullings, R. S. Goodridge, G. A. Hathaway, Joseph Jacobs, Prof. F. T. Mavis, H. S. Riesbol, Waldo E. Smith, F. F. Snyder, and H. G. Wilm. The Committee represents a rather wide geographic distribution, quite a large variety of interests, and most of the agencies interested in runoff-problems.

Throughout the year members of the Committee have shown interest in runoff-problems of various kinds as evidenced by numerous articles and discussions in technical publications and by their participation in the deliberations of many working or advisory committees dealing with hydrologic problems. As the Chairman views it, the functions of the members of the research committees are not only to keep abreast of, and to make advances in, the technique relating to their particular fields, but also to demonstrate the practicability of the technique in the field of applied hydrology. Members of the Committee on Runoff have kept these aims in view. As in past years, the Committee is indebted to Miss Mary Soroka of New York City, Chairman of the International Committee on Bibliography, for her compilations of references to all articles relating to runoff, and to Mr. Beij for his work in connection therewith.

As appendices to the Chairman's report of last year, there were included detailed lists of experimental areas and watersheds on which observations of rainfall-runoff and silt-losses were being carried on by the Soil Conservation Service and by the Forest Service. These areas have remained essentially unchanged during the year. During the year the Soil Conservation Service have inaugurated a series of processed reports entitled "Hydrologic studies: A compilation of rainfall and runoff" in which basic data for their various areas are being compiled and published as expeditiously as possible. The United States Geological Survey has continued its general hydrologic studies of floods and droughts, and during the year published Water-Supply Papers 842, "The Pecos flood of June 1937," 796-G, "Major Texas floods of 1935," and 843, "Floods of December 1937 in northern California." Water-supply papers are also in course of preparation relating to the flood of March 1938 in southern California, the hurricane-flood and ocean storm-wave of September 1938 in New England, the Muskingum flood of August 1935, floods of January and February 1938 in New England, cloudburst-floods in Colorado, cloudburst-floods in Utah, and reports on hydrologic conditions in Iowa, Florida, Missouri, Kansas, South Dakota, Oregon, and Washington.

Members of the Section should be interested in the progress-reports and articles published as follows in the Proceedings of the American Society of Civil Engineers: The report of the Hydraulics Division on Flood Control (April 1940); "The unit hydrograph principle applied to small watersheds" by E. F. Brater (September 1939); "Transient flood peaks" by Henry P. Lynch (November 1939); and the progress-report by the Committee on Flood Protection Data (April 1940) The Water Resources Committee of the National Planning Board have just issued an exhaustive report relating to deficiencies in hydrologic research prepared by a committee on which the Section of Hydrology was well represented. F. F. Snyder, a member of the Committee on Runoff, has made detailed hydrologic studies in Pennsylvania which have been incorporated in a cooperative report by the Pennsylvania Department of Forest and Waters, Weather Bureau, and Geological Survey. Many members of the Section have taken an active part in the hydrological studies being carried on by the Corps of Engineers directed by G. A. Hathaway, and the associated meteorological studies in the Weather Bureau directed by Merrill Bernard, in connection with limiting storm- and flood-possibilities. Other members of the Section and of the Committee on Runoff have been interested in hydrologic problems involved in flood-control studies carried on by the Department of Agriculture through its Flood Control Coordinating Committee. Special mention should be made to the Hydraulics Conference held at the University of Iowa, June 12-15, 1939, under the auspices of the Society for the Promotion of Engineering Education and the Iowa Institute of Hydraulic Research. This meeting was conceived and the program directed by Professor F. T. Mavis. Proceedings of this outstanding conference are published as Bulletin 20, Studies in Engineering, University of Iowa.

During the year, members of the Committee on Runoff were represented on an interdepartmental committee to formulate methods for evaluating rainfall-runoff indices and relations. This committee was composed of representatives of the Corps of Engineers, Soil Conservation Service, Forest Service, and Geological Survey. The writer is convinced that to a greater extent than ever before more people are engaged on studies of hydrologic phenomena relating to runoff and in the application thereof to practical problems.

As during the past several years, the Committee on Runoff held an all-day informal round-table discussion on Saturday, April 27, 1940. This year the round-table discussion was held jointly with the Infiltration-Committee of which Mr. Musgrave is Chairman (see notes on Joint Round-Table in these Transactions).

U. S. Geological Survey,
Washington, D. C.

COMMITTEE ON SNOW, 1939-40

J. E. Church, Chairman

The last report on snow emphasized the growth of snow-surveying for the forecast of water-supplies and its acceptance as one of the must activities of the Mountain States and the Federal Government. The present report will emphasize growing interest in the conditions under which maximum floods occur and in forecasting their imminence.

The general field of snow-studies is expanding normally with its wide variety of projects.

Personnel and field

The Committee now has 35 members representing the United States, Canada, and Newfoundland. Each of these numerous members has added his contribution to the work of the Committee. To give each a narrower specialty along the line of research interests, the Committee has been sub-divided into special sub-Committees as follows: Water-Supplies; Evaporation; Floods; Snow-Cover; Physics of Snow and Ice; Transport; Regional Representatives. The members of the sub-Committees are urged to maintain broad interest. There is no restraint geographically.

For purpose of permanent record and reference the complete list of the Committee's membership is given below.

Officers

J. E. Church (Chairman), Meteorologist, University of Nevada Agricultural Experiment Station, Reno, Nevada

R. C. Farrow (Vice-Chairman), Hydraulic Engineer, Water Rights Branch, Department of Lands, Victoria, British Columbia, Canada

Carl H. Elges (Secretary), Assistant Meteorologist, University of Nevada Agricultural Experiment Station, Reno, Nevada

Water-supplies

W. W. McLaughlin, Chief Division of Irrigation, Soil Conservation Service, Box 180, Berkeley, California

L. K. Sherman, Consulting Engineer, 53 West Jackson Boulevard, Chicago, Illinois

H. K. Barrows, Professor Emeritus of Hydraulic Engineering, Massachusetts Institute of Technology, Boston, Massachusetts

Evaporation

Joseph Kittredge, Jr., Professor of Forestry, University of California, Berkeley, California

François E. Matthes, Senior Geologist, U. S. Geological Survey, Washington, D. C.

Floods

Merrill Bernard, Supervising Hydrologist and Service Coordinator, U. S. Weather Bureau, Washington, D. C.

G. A. Hathaway, Senior Engineer, War Department, Washington, D. C.

Gerard H. Matthes, Member, Mississippi River Commission, Vicksburg, Mississippi

Snow-cover: Physics of snow and ice

Bestor Robinson, Chairman, Winter Sports, Sierra Club, Oakland, California

Dr. Henry I. Baldwin, Assistant Forester for Forest Research, Hillsboro, New Hampshire

Salvatore Pagliuca, Chief Meteorologist, The Yankee Network, 21 Brookline Avenue, Boston, Massachusetts

Howard T. Barnes, Professor Emeritus of Physics, Queen City Park, Via Burlington, Vermont

Phil E. Church, Assistant Professor of Geography and Meteorology, University of Washington, Seattle, Washington

Robert G. Stone, Librarian, Blue Hill Meteorological Observatory, Milton, Massachusetts

Transport

Lacey V. Murrow, Director of Highways, State of Washington, Olympia, Washington

Regional representatives

Paul L. Bean, Agent and Engineer, Union Water Power Company, Lewiston, Maine

E. S. Cullings, Secretary, Black River Regulating District, Watertown, New York

D. B. Freeman, Engineer, War Department, Missouri River Division, Kansas City, Missouri
James C. Marr, Irrigation Engineer, Box 835, U. S. Conservation Service, Boise, Idaho
E. B. Debler, Hydraulic Engineer, U. S. Reclamation Service, Denver, Colorado
Harlowe M. Stafford, Counselor, Water Resources Committee, National Resources Planning Board, Roswell, New Mexico
Dean George D. Clyde, College of Engineering, Utah State Agricultural College, Logan, Utah
H. P. Boardman, Professor Emeritus of Civil Engineering, University of Nevada, 735 West Street, Reno, Nevada
Fred H. Paget, Associate Hydraulic Engineer, Department of Public Works, Division of Water Resources, Sacramento, California
J. H. Ryan, Assistant State Engineer, In Charge Oregon State Snow Surveys, Salem, Oregon
E. H. Collins, Assistant Chief Engineer, Washington Water Power Company, Spokane, Washington
R. A. Work, Associate Irrigation Engineer, Box 1149, Medford, Oregon
Eric Hinton, Engineer, International Power and Paper Company of Newfoundland, Deer Lake, Newfoundland
Matthew Balls, The Shawinigan Water and Power Company, Montreal, Canada
O. H. Hoover, Engineer-in-Charge, Dominion Water and Power Bureau, Calgary, Alberta, Canada
William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan
Laurence M. Gould, Professor of Geology and Geography, Carleton College, Northfield, Minnesota

Cooperating organizations

The organizations cooperating closely in the development of snow-surveying are steadily increasing in number and represent every division of civic organization from Service Companies to the State and Federal Government. Twenty-four are now purchasing reprints of the Western Interstate Snow-Survey Conference and the Report of the Committee on Snow for distribution. Data are freely interchanged. There is little attempt at refusing consultation or data for general use. A happier condition for advancement in hydrology could hardly exist in America, especially in view of the breakdown or destruction of scientific organizations abroad.

The Western Interstate Snow-Survey Conference which has always been an open forum for the presentation of research problems and discussions and the Research Advisory Committee of the Soil Conservation Service established by the Section of Hydrology of the American Geophysical Union have been instrumental in bringing this cooperative spirit into being.

The season and snow-cover

The 1940 season was characterized by continued cold in the Eastern States and mild weather with rain in place of snow in the Western. This condition is well described in the following reports:

(I) Snow favors cold and fair weather, by Charles F. Brooks [Bull. Amer. Met. Soc., April, 1940]--"A few days before Christmas a cold wind set in over the eastern United States, and battling with a warm one from the Gulf of Mexico laid down a deep blanket of snow from Missouri eastward across Kentucky and the Virginias to the Atlantic seaboard. To the north the ground remained bare despite the forecasters' utmost efforts to give us a 'white Christmas.' The cold wind kept on blowing strongly from the west and northwest over New England, maintaining hurricane-velocities across Mt. Washington, and bringing southeastern New England under a descending wind and hence keeping it snowless.

"As soon as the sky cleared over the snow-covered area the temperature dropped rapidly, for neither could the heat from the ground get to the air at all readily nor could the sunshine warm the surface of the snow appreciably . . . .

"The chilling effect of the snow was not confined to the snow-covered area. The air over the snow contracted on being chilled permitting air from surrounding regions to flow in overhead. This raised the pressure at the ground over the snow-belt and lowered it on both sides. So the cold air flowed northward and southward, particularly the latter, for the general temperatures there were higher and the pressure less. The Weather Bureau's map of the mean temperature for the week showed an extension of the cold area to several hundred miles south of the snow belt." Thus arose the conditions that froze highways in the south and accumulated snow in the north.

In the West the report of the condition of the snow-cover in the Sierra Nevada is representative for most of the watersheds.

(II) Seasonal forecast of stream-flow, by Fred H. Paget [California Cooperative Snow-Surveys, April 10, 1940]--"We have in the Sierra today a condition of snowpack disposition differing from any that has been recorded since the beginning of the present snow-measuring program

that began ten years ago; at elevations above 7,500 feet a snowpack above normal with an almost complete absence of snow in the wide belt between the 5,000- and 6,000-foot contours usually well covered at this time of the year.

"This is due entirely to the warm storms that have characterized this winter's weather. Storm after storm swung into the mainland from the Pacific Ocean by way of the Hawaiian Islands bringing with them the warm air of the tropics. The high temperatures consistently discouraged snow below an elevation of 6,000 feet when ordinarily the lower limit of snowfall is at least 1,000 feet lower down, to about the 5,000-foot contour. Even at mid-winter the rains at times prevailed up to as high as 7,500 feet, higher than the Donner Summit, on the main transcontinental route from San Francisco to the East. At elevation 7,500 even the warm storms cooled down to temperatures conducive to the deposition of snow and above that elevation each storm added to the snow-blanket.

"This accounts for the lighter snowpack in the northern watersheds where elevations above 7,000 feet are very limited, and explains the better pack in the southern Sierra where areas above 7,000 feet are quite extensive."

The water-supply in the West is approximately 75 per cent, except in the Southwest where shortage is acute. There will be sufficient water in most places where storage-reservoirs exist.

Regional reports

To the general picture given above are added the following details pertaining to the various regions:

Newfoundland (ERIC HINTON)

"The effect of the unusually mild winter, produced no ice-cover on the main body of Grand Lake. Consequently, the survey-party was transported around the Lake by one of the small diesel tugs. Excursions were then made, from various points along the shore, into the hinterland, for the purpose of obtaining the snow-observations.

"During the past 15 years (1926-40) Grand Lake was practically free of ice only in the winter of 1930-31, 1935-36, and 1939-40. And in the winter 1936-37 Grand Lake was frozen over only for a distance of three miles from the northern end.

"Although Sand Lake was entirely frozen over, the ice was mixed with snow so that it was impossible to obtain any satisfactory observations of ice-thickness. The condition of Sheffield Lake was similar. In fact the ice was so inferior that it was considered unsafe to stop the dog-team while moving across these lakes.

"Nevertheless, conditions of transportation, both by tug and dog-team, were so satisfactory, that the survey was conducted much more rapidly than usual, and more important, the survey was complete.

"The estimates indicate that the flood (that is, spring) runoff will produce a high-water level of only elevation 373.5. This is five feet below the full capacity of the Reservoir. Consequently, even with an abnormally heavy rainfall during the flood-interval, there can be no risk of having to spill any water.

"It is apparent that a programme of water-conservation should be followed until July 1, at least. It is proposed, therefore, that the Power-Station be operated at maximum efficiency (that is, a station-load of 95 to 98 MW) until power requirements can be more clearly defined and the effect of summer rainfall becomes known.

"During the 14-year period of 1926-39, the estimate of runoff for nine years or two-thirds of the period has been within 10.2 per cent of the actual. The divergence during the other five years is as follows: 12.2, 15.1, 16.9, 26.2, 28.5 per cent."

New England (PAUL L. BEAN)

"Following is a general summary of work on snow- and ice-covers for the State of Maine, with particular attention to the Androscoggin River Basin in Maine and New Hampshire.

"Snow-surveying to a greater extent than usual is being carried out by the United States Geological Survey Office in Augusta, by Bryant L. Hopkins in Waterville, and the Union Water Power Company in Lewiston.

"The United States Geological Survey office has carried on work in the following drainage-areas: Kennebec; Saco; Androscoggin; Penobscot; Union; Machias; St. Croix; and St. John rivers. They have also obtained ice-measurements on the St. John, Penobscot, Kennebec, and Saco river-basins and a few coastal streams. Mr. Hopkins has taken rather extensive measurements in the Kennebec River-Basin.

"This office (the Union Water Power Company) has taken extensive measurements throughout the Androscoggin River-Basin at various times during the winter and has kept a close account of the increasing snow-cover. Also several ice-measurements have been obtained from various industrial concerns along the River, who are very generous in cooperating with this Office.

"Excellent results have been obtained by using and applying the measurements taken to the practical problems which arise in respect to use of water from storage-reservoirs and the water from the uncontrolled area that produces flood-conditions in this and other valleys.

"Experiments were made last year with the Mount Rose sampler and the regular sampler used by this Company to determine which would be the better for use in the work in this area. The results obtained were convincing. The Mount Rose sampler appears to be inadequate for use in this section.

"From data obtained by a comparison of readings taken with the two samplers an error of up to 44 per cent was noted when two adjoining samples were measured. The Mount Rose sampler showed the lower water-content of the two samples, the size of the error depending on the texture of the snow. The coarser the snow (approaching "corn-snow" so-called), the larger the discrepancy shown by the Mount Rose sampler. It is believed that the error is due to loss of snow through the slots for determining the length of core and possibly to the small diameter of the sampler itself.

"Some progress has been made in the study of the snow under the magnifying glass, but this work has not yet advanced to a point where accurate and useful data can be submitted.

"For the winter of 1939-40 the precipitation in this section has been considerably below normal, with the result that the snow-cover with its water-content has been below the average for the past 29 years as of March 1. However, to date in March, the occurrence of several storms has built up the water-content of the snow to a point where continued rain and warm weather combined with the rather heavy ice-cover on the Androscoggin River, would present serious flood-conditions on the River.

"Storage-reserves for the winter have been below normal. Since January, the ground has been extremely dry with very little ground-water reaching the River. The forest-floor has been and remained frozen for the first time in many years. Usually the ground around coniferous trees is not frozen, while there usually is frost around the deciduous trees and in the fields. This year it has been noted, while measuring snow, that each station shows frost in the ground with the exception of about five stations out of a total of 49, where this characteristic was noted.

"It may be said in general that snow-surveying and ice-measuring in this State, and in the Androscoggin Valley in particular, is being expanded from year to year. The importance of this work is being more fully realized and it is hoped that in the not too distant future data of some value may be submitted for study and compilation."

New Hampshire (HENRY I. BALDWIN)

"We have a good snow-cover here (March 11) of about three feet, increasing to four to six in the mountains. Until recently the temperature has not been above freezing at Pinkham Notch since early December except once for a few hours only so that the snow in this vicinity is still dry, packed powder.

"The recreational use of snow for skiing has increased still further in New England and New York. A recent survey by the New Hampshire Planning and Development Commission showed increases of 25 per cent in use of recreational areas and income from business connected with winter sports in New Hampshire. Increase of local manufacture of skis is presaged by the recent prohibition of ski-export by Sweden and threatened similar action by Norway."

New York (E. S. CULLINGS)

"I am sending you a map of the Adirondack Region, showing the water-content of the accumulated snow on March 18 and 19, 1940. The past winter has been a long, cold one, with almost no thawing, and the snow-cover has reached record depths in several areas."

Continental Divide (HARLOWE M. STAFFORD)

"Acknowledging your circular letter of March 1 and appended note to 'give us a view of the Southwest,' I am sorry that I am unable to give much of a report for the Southwest. I have had little opportunity to keep in touch with snow-surveys and forecasting for this region, and hence cannot at this time offer any suggestions for improvements in the surveys and procedures, or for additional research projects which might be needed. Since all of the surveys and forecasts for this region clear through Mr. Parshall of the Division of Irrigation, Soil Conservation Service, at the Colorado Agricultural Experiment Station, Fort Collins, Colorado, he is in a much better position than I to make such suggestions and recommendations.

"The only information I have on forecasts for the season of 1940 is through the bulletins received from the Division of Irrigation, Soil Conservation Service. Summarizing the data of these, as issued on March 10, the outlook for the Southwest on March 1st was about as shown in Table 1.

"Table 2 and comments from the forecast by Mr. Parshall for April 1 afford a wider and later picture of water-conditions in this area.

"There has been a loss of surface soil-moisture in the valley areas during the month, and in the irrigated section on the Salt and Gila rivers the surface-soil is dry. Subsoil-moisture is also deficient. Storage in the Salt River Water Users Association reservoirs is less than half

Table 1

Stream-basin	March 1, 1940 Snow-water content in per cent		Remarks
	Of 5-year average	Of 1939 content	
North Platte	87	82	Subsoil deficient in moisture; stream-flow and reservoir-storage below normal
South Platte	105	63	
Arkansas	74	63	
Rio Grande	90	90	Stream-flow and reservoir-storage below normal
Canadian	126	132	
Upper Colorado	81	71	Surface soil-moisture fair
San Juan	91	97	Subsoil-moisture deficient
Gila	73	39	Accumulated deficiency in precipitation on watersheds of Gila and Salt rivers in Arizona and deficiency in reservoir-storage indicate a serious water-shortage in 1940 unless there is marked improvement in precipitation in March and April

Table 2

Stream-basin	Snow-water content April 1, 1940, in per cent	
	Of 5-year average	Of 1939 content
Headwaters of Missouri River	80	86
North Platte	81	83
South Platte	82	82
Arkansas	77	74
Rio Grande	63	93
Upper Colorado	80	78
Green	89	100
San Juan	50	70

of what it was last year at this time. There are only 50,000 acre-feet in Coolidge Reservoir. Stream-flow increased during March in the southern areas due to melting snow, but as the snow is fast disappearing, the flow will diminish rapidly.

"Below normal precipitation and deficient snow-cover together with the shortage of both surface- and subsoil-moisture make the outlook for irrigation-water this summer very disturbing, particularly in the Salt and Gila river-valleys in Arizona. On the watershed of the Colorado River in Colorado, the runoff will probably not exceed 75 per cent of what it was last year if precipitation from now on is normal, but if there is a shortage of precipitation a more serious reduction in runoff will occur. Conditions are more favorable on the Green River and on the Colorado River in Utah. The outlook there is for a runoff similar to that which occurred last year."

Utah (Summary of forecast by GEORGE D. CLYDE)

"A detailed analysis shows that the snow-cover on the watersheds of Utah this year is very spotted, that it contains on most areas considerably less water than last year, that the low snow-cover has melted off all of the watersheds, and that in general the soil under the high cover is dry. Watershed-yields in general will be less per unit of snow-cover because of the deficient fall precipitation which usually primes the soil and because of the early melting of the low snow-cover. On April 1, 1940, the discharge of the major streams in the State was less than on the same date in 1939 in spite of the early melt of the low snow-cover.

"The supply of storage-water this year will not be as great as it was in 1939, but the amount of storage available will fully provide in most cases for the 1940 demands of those holding storage-rights or a combination of storage- and natural flow-rights.

"Due to the absence of low snow on all the watersheds, usually high water during the spring runoff-period is not to be expected. However, high runoff for a few days is possible if a combination of temperature and spring precipitation develops which will melt the high snow at a rapid rate. All owners of reservoirs should, therefore, examine their spillways and outlet works, clean and repair their trash-racks, and see that their gate-operating devices are in working order."

California (FRED H. PAGET)

"The measurements of snow-cover indicate that for the Sierra as a whole, there is this year

about three-quarters of a normal snow-pack. It insures ample water for all of California's needs for the coming summer and carries little threat of floods even at the peak of the snow-melting period. Because of above normal quantities of snow at high elevations, late summer flows should be good."

The significance of deep snowfall for snow-sports is indicated in the following clipping from the San Francisco Chronicle (March 16, 1940):

"Yosemite National Park--Heavy snowfall in the high country of Yosemite this season promises abundant waterfalls and wild flowers this spring, according to Lawrence C. Merriam, Park Superintendent. While the lower elevations have received heavy rains the areas above 7000 feet elevation have a good snow-pack.

"Snow-depth at Badger Pass ski-fields is now 68 inches as compared with 54 inches last year, assuring good spring skiing for weeks to come. Precipitation in Yosemite Valley to date since July 1 is 35 inches as compared with a normal of approximately 25 inches."

Oregon (J. H. RYAN)

"The February 1 and March 1 snow-measurements were very disappointing from the standpoint of water in storage for summer needs, and our April 1 measurements were not very much more encouraging. While continued cold weather and rain have hindered farm-work in the northeastern portion of the State, the unusually heavy rains, which have been general throughout the whole State, have been especially beneficial to the dry-farming areas and the open range. More springs fed from deeply percolating waters are now flowing than has been the case for many years.

"The advancement of the growing season shows wide variations. In the northeastern section the season is probably three weeks behind normal. In the central and southern portions it is about normally developed, while the Willamette Valley and coastal region are from three to four weeks ahead of normal.

"At the time of the meetings of our Water-Forecast Committee due consideration was given to the probable effect on runoff of the unusually heavy precipitation in the form of rain which occurred at all elevations during the early winter, and an attempt was also made to evaluate the effect of the abnormally heavy ground-storage in increasing the sustained low-water flow.

"It now appears that we were fairly successful in forecasting the flow of streams with watersheds having low elevations, but the stream-basins having a considerable area lying at higher elevations are consistently delivering more water than was estimated.

"The factor which has upset our forecasts is the continuation of the rains which normally would cease about April 10 or 15 throughout most of the State, but which this year have continued up to the present time (May 6) and still show no signs of a let up.

"It is to be expected that stream-flow will diminish sharply when the rains stop, but soil-moisture conditions are now so favorable that the demand for irrigation-water will be light until at least the first part of June, which will mean a correspondingly larger hold-over of water stored in reservoirs.

"Dry-land farming- and range-areas are in excellent shape and winter-sown wheat is growing exceptionally well."

Columbia Basin (JAMES C. MARR)

"Storms during abnormally warm weather in January replenished the soil-moisture and ground-water deficiencies that existed throughout the Basin last fall. Most of the winter's snowfall occurred during February. In March the precipitation occurred again as rain, excepting at the highest altitudes. The results are: A fairly satisfactory snow-pack is left as of April 1 on the relatively small mountain areas ranging above 5,000 to 6,000 feet elevation; all of the lower snow-cover has disappeared; the runoff so far has been considerably larger than usual; and the soils and subsoils of all watersheds as well as the agricultural areas are well primed with water.

"Under these conditions the snow-pack may be expected to produce gradual runoff rather than freshets of material size or duration. A moderate increase in runoff, at most, this spring followed by early return to low river-stages and low but well-sustained summer stream-flow appears certain if normal weather-conditions prevail during the next few months.

"The early runoff considerably increased the total amount of reservoir-water. The amount now nearly equals that of 1939, which was a banner year in that respect."

British Columbia (R. C. FARROW)

"In accordance with your circular letter of March 1, 1940, the following may be of interest for the annual report of the Committee:

"A comparison of forecasts and actual runoff was sent to the Chairman of the Western Interstate Snow-Survey Conference meeting at Berkeley, California, in January 1940. I see I did not give quantitative figures of runoff, so in case you would like them they are tabulated in Table 3.

Table 3

Area	Stream, name	At	No. of courses involved	Runoff April-August in acre-feet		Error in per cent of actual
				Forecast	Actual	
Coastal	Stave River	Stave Falls	3	1,339,000	1,180,000	+13.5
	Powell River	Powell Lake	2	830,100	1,140,500	-27.2
Kootenay	Lardeau	Gerrard	1	430,400	492,000	-12.5
	Duncan	Howser	1	1,503,000	1,743,000	-13.8
	Elk	Elko	2	1,077,000	912,000	+18.1
	Slocan	Crescent	1	1,682,000	1,623,000	+ 3.6
	Kootenay	Wardner	3	3,578,000	3,405,000	+ 5.1
	Kootenay	Glade	5	14,825,000	14,160,000	+ 4.7
Okanagan	Okanagan	Penticton	5	379,800	225,700	+68.3
Columbia	Columbia	Golden	3	2,016,000	1,951,000	+ 3.3
Columbia	Columbia	Revelstoke	6	16,832,000	16,828,000	+ 0.1
	Columbia	Trail	14	35,884,000	34,680,000	+ 3.4

"Unusual conditions of water-resources in British Columbia--This has been a most "unusual" winter throughout all of British Columbia.

"The past winter has been abnormally mild throughout most of British Columbia, a condition which has prevented anything like the normal accumulation of snow, of which to date there is an alarming shortage in many areas.

"In the Coastal Belt (west of the Coast Range Divide) the precipitation since November 1 has on the whole been well above average but the high prevailing temperatures have induced rain at altitudes which normally receive snow, with the result that the snow-covered area is far smaller this year than usual, and while accumulation does increase with altitude it is far below normal at all elevations. For example on Grouse Mountain Plateau, opposite Vancouver, elevation 3,800, there were only one and one-half feet of snow on the ground on January 31 where there are normally 11 feet and three and one-half feet on February 29 instead of 13 or 14 feet. This is a favorite skiing ground for Vancouver enthusiasts, and no skiing was possible this year until late in February. On Dam Mountain, in the same area, elevation 6,500-7,000, there were five feet of snow on January 31 instead of about 15 feet, and on February 29, nine feet instead of about 20 feet. The total precipitation on Grouse Mountain Plateau from November 1 to February 29 was 31.02 inches, but only 4.1 inches (water-equivalent) of this fell as snow.

"In general I estimate that at this time water stored in the form of snow on the Coast Range is only about 30 per cent of normal.

"It is not generally realized that even our wet Coastal Belt is dependent on snow-melt for summer runoff on the streams used for domestic supply, hydroelectric generation, and for several large pulp and paper mills which are large users of water. A shortage of snow in the Coast mountains is therefore a serious matter.

"In the interior of British Columbia, and in particular, the Kootenay and Columbia basins the same general conditions obtain. The winter precipitation on the average has been rather below normal, but a far greater proportion than usual has come in the form of rain instead of snow, even at comparatively high altitudes. In addition there has been intermittent thawing throughout the winter; streams have flowed well above average; so that the accumulation of snow has been well below normal. The highway snow-plows have hardly left their sheds this winter.

"It is expected therefore, unless there is abnormal snowfall from now on, plus a very wet summer, that all streams will produce a summer runoff considerably below average."

Alberta (O. H. HOOVER and W. T. McFARLANE)

"In reply to your letter of March 1, 1940, to members of the Research Committee on the Hydrology of Snow, American Geophysical Union, I wish to submit herewith a synopsis of the results obtained from seven snow-courses, on our annual snow-survey, on the Bow River in the vicinity of Lake Louise, Alberta. From this synopsis we predict a runoff for the period April 1 to July 31, 1940, of about 82 per cent of normal in this area.

"Our snow-survey on the St. Mary River is not obtained until the first week in May and accordingly I am unable to supply any data for that area at the present time.

"Synopsis of Bow River snow-survey on seven courses, made near Lake Louise, Alberta, Canada, in March 1940--Courses 2 and 4 were inspected on March 28, courses 5, 6, and 7 on March 29, and courses 1 and 3 on March 30, comprising 125 samples.

"The results of Tables 4-A and 4-B were obtained.

Table 4-A--Summary for survey of March, 1940

Course	Mean snow-depth,	Mean length of core	Mean water-content	Snow-density
	inch	inch	inch	per cent
1	22.3	13.1	5.2	23.3
2	25.9	12.8	5.6	21.6
3	18.5	9.0	3.8	20.5
4	22.9	8.6	5.3	23.1
5	25.6	10.5	5.5	21.5
6	34.0	13.2	6.6	19.4
7	30.2	12.6	5.6	18.5
Totals	179.4	79.8	37.6	147.9
Means	25.6	11.4	5.4	21.1

Table 4-B--Summary for years of survey

Year	Mean snow-depth	Mean length of core	Mean water-content	Snow-density
	inch	inch	inch	per cent
1937	19.7	9.1	3.8	19.6
1938	36.2	18.2	8.1	22.0
1939	17.6	15.2	6.2	36.3
Means	24.5	14.2	6.0	26.0

"The mean water-content from the seven courses in 1940 of 5.4 inches compares with 6.0 inches representing the average content for the former three years of the survey.

"From the data obtained in March, 1939, it was predicted that the runoff for the Bow River at Banff for the following April, May, June, and July would be 587,000 acre-feet. The measured stream-flow figures for this period proved to be 556,550 acre-feet, or about 94.8 per cent of the estimate. The average water-content of 5.4 inches obtained on seven courses in March, 1940, is estimated to produce about 550,000 acre-feet of runoff for April, May, June, and July on the Bow River at Banff.

"The average runoff for these four months, on the Bow River at Banff, for the past 30 years has been 669,600 acre-feet. This year's prediction is therefore about 82 per cent of normal. Heavy rains in June may however occur and these for any season may materially affect the estimate calculated from the snow-survey."

International: Montana-Alberta (C. S. HEIDEL and W. T. McFARLANE)

"The experience in the St. Mary River Drainage-Basin, where joint snow-surveys and forecasts have been conducted by the United States and Canada since 1922, has taught that snow has attained its maximum water-content early in May. Near this date the ice in the lakes, lying in an altitude between 4,000 and 5,000, begins to move out, and the flow in the streams to be increased by the melting of the snows at the lower altitude.

"In addition to the actual snow-samples, lake water-levels, stream-discharge, and numerous photographs taken from camera stations give much additional valuable information. But it must be remembered that in estimating the water-value of snowfall, superficial appearances and depth only are unreliable and that photographs may actually be deceiving.

"Altitude plays an important part in the collection and retention of snow and Table 5 is prepared to show the percentage of the St. Mary Basin above Babb which lies at the various altitudes. It will be noted that the area which lies above 8,000 feet and which is not covered by actual measurements during the snow-survey, represents only a small portion of the whole area, although the snow-quantity in this section is, no doubt, in excess of that found at the lower elevations.

Table 5

Area	Square miles	Percentage of total area
Total area of Basin above Babb	278	100
Area below elevation 5,000 feet	70	25
Area between 5,000 and 6,000 feet	86	31
Area between 6,000 and 7,000 feet	64	23
Area between 7,000 and 8,000 feet	45	16
Area above elevation 8,000 feet	13	5

"For the year 1940 both the depth of snow and water-content are less than the mean for the previous 18 years of record. The estimated probable runoff during May to July is 57,640 acre-feet."

Snow-surveying and forecasting

Improvement in forecasting must now be made perforce because of the great lack of snow-cover at lower elevations, which entered in earlier years into the estimate of water-supplies. The zonal method of adjustment, long foreseen and developed for emergency, must now be put to its extreme test.

Steady development has been made in improving the snow-courses in the Great Basin to meet the obstacles of shallow snow, fewness of precipitation and stream-gaging stations, and diversion of water practically to the head of the streams.

New courses long planned are now being adapted to both slopes of the Cascade Range.

A system of forecasting water-supplies has been requested for the higher elevations of the Colorado River tributaries to serve the irrigable lands in Western Colorado.

At the request of the Biological Survey, snow-courses have been established for determining snow-cover conditions in the wild-life refuges to plan more exactly for winter feeding and summer water-supplies.

The latest advance in snow-surveying reported is the use of surveys of the snow-cover in Utah as a basis for estimating and apportioning underground water-supplies. A project is now under way in southern Nevada to seek a relationship between the snow-cover in the Charleston Range and the artesian flow in its neighborhood.

The United States Weather Bureau under the supervision of the River and Flood Division is installing a network of snow-gages at higher elevations throughout the country. The progress in this work is reported by Merrill Bernard as follows: "There are approximately 1,300 stations measuring snowfall, with an average elevation of 4,174 feet. The network of mountain snowfall-stations equipped with batteries of shielded snow-gages now numbers 92, four of which are below 5,000 feet, 46 between 5,000 and 8,000 feet, 37 between 8,000 and 10,000 feet, and five above 10,000 feet. The average elevation of the 92 stations is 7,643 feet." This system has now reached the Pacific Coast. Regional hydrologic supervisors have been appointed to direct measurements.

Quantitative snow-surveys

In the East quantitative snow-surveys have been made from the beginning in order to adjust the estimate of water-supplies better to mid-winter losses of snow. In the Androscoggin Basin of New Hampshire, Maine, Charles E. Mixer, at the turn of the century, originated the idea of estimating spring freshets from the water-content of the snow-cover. In that Basin, Paul L. Bean by the use of snow-sampling has estimated both normal river-flow and even the great flood of 1936 within an accuracy of five per cent.

In Manchester, New Hampshire, John V. Salo for the Public Service Company of New Hampshire has established snow-surveys at the mean elevation of the snow-cover to reduce the number of snow-courses otherwise required. However, he is establishing courses at various levels also to compare the value of zonal forecasting as compared with that of the mean elevation only.

During the past winter an attempt was made to estimate the snow-cover of the Connecticut Basin from train. This reminds one of the habit of the early settlers of Nevada on the Humboldt Basin of traveling to its headwaters to observe the snow-line on the mountains. In Minnesota flood-surveys are being planned by precipitation-gage and snow-sampler by Carlos G. Bates, pioneer in the study of the Conservation of Snow, particularly at Wagon Wheel Gap, Colorado.

Floods

A long-desired trip to the northeastern States following the International Association of Scientific Hydrology at Washington, D. C., in September 1939, revealed the value of even a shallow snow-cover to seasonal runoff and its major influence on the summer flow as compared with scattered summer rains.

A trip to the Tennessee Watershed, now under hydrologic development, seems also desirable in order to study the effect of snow-cover in this Basin if any exists. This Basin should at least be valuable in the study of the relative effectiveness of snow and rain.

The Northeast seems to be the home of the flood. The Susquehanna Basin is its chief exponent. As Carroll F. Merriam, Manager of the Pennsylvania Water and Power Company, states, they have "approximately ten per cent of the total flood-damage of the entire country in a drainage-area that is not much more than one per cent of the total." The reason for this is obvious in the shallow soil-cover, underlaid by slate (as effective almost as a roof) and the heavy precipitation of approximately 40 inches resulting from over-passing cold continental air-masses from the North and the moist air-currents from the South. The deciduous forests which dominate the region provide little protection against melting of the snow, and frost adds to the imperviousness of the soil, particularly where the surface is wind-swept.

However, it seems probable that frost does not usually exist beneath the deeper snow. The

problem of the relationship of forests to the occurrence of frost is being studied by the organizations now cooperating under the flood-control act. It is possible that the frost which occurs early in the autumn may be eliminated by Earth-warmth, providing the snow-cover is sufficiently deep to withstand further penetration by the cold.

Dr. Horton has noticed for New York State that major floods seldom occur when the snow is deep. This is substantiated by the fact that rain at even 50° F melts only one-eighth of its weight of snow.

In Michigan and Wisconsin, floods are reported as rare because of the depth of glacial covering and the under-soil pockets of the Region and the lakes, assisted by increasing remoteness from the rain-belt.

In the West torrential rains appear to be the chief cause of floods. An extreme example is the report of 17 inches rain in 11 hours at Brookdale in the Santa Cruz Mountains, California, the present year by which redwood trees were uprooted. This probably occurred at the time (March 30) when a downpour of 4.16 inches in 24 hours was recorded at adjacent Santa Cruz at sea-level.

At Scales (Stramberry Valley) 4,300 feet elevation in the Sacramento watershed a total precipitation of 19.98 inches was recorded for March 24-31 with individual records of 4.60, 4.85, and 5.37 on March 26, 29, and 30, respectively. Maximum floods, however, would probably be the result of the melting of large areas of shallow snow in the vicinity of the snow-line or covering the valley-floor below.

Such was the destructive flood of early March, 1910, in the Humboldt Basin, Nevada, caused wholly by the slow accumulation of snow during a cold winter and its sudden melting by an abrupt rise in temperature. More cogent still is the fact that the total precipitation during December to February was only 82 per cent of normal upstream and 135 per cent downstream, while during the progress of the flood, February 25 to March 12, no precipitation was reported from Elko and only 0.07 inch from Winnemucca, near the two ends of the Basin. The depth of the snow-cover at the lower elevations was two feet, increasing to twice that depth at 7,500 feet and to three times at 8,000 feet. The density of the snow was doubtless 25 per cent or an accumulation of six inches water-content on the basin-floor.

The great snow-fields at higher elevations are probably impregnable to all but the heaviest rains and highest temperatures. Thus the maximum flood now being sought by the Army Engineer Corps should not be based upon the snow-storage of the mountains but rather upon continued and heavy storms. The flood-crest of the Sacramento River, "the highest of record," probably failed to attain a greater height because of the absence of snow-cover in the flood-zone. On the other hand, if the snow-cover had been heavy in this zone, the crest would probably not have attained its extreme height. The major depth of snow in the East the present season and its lack at lower elevations in the West should afford an opportunity to study snow-effects on floods. Supplementary elements in this study will be temperature and rainfall-intensity. The flood in the Susquenanna in early April and that in the Sacramento in early March were both high but in the East less high and widespread than the destructive flood of 1936.

A detailed study of the flood of 1940 in the Tahoe-Truckee Basin has been made by the Chairman in response to a questionnaire from Major R. H. Elliott of Bonneville, Oregon, regarding the optimum conditions for maximum floods.

Ice in rivers is a problem in itself and is receiving increased study.

Conservation

Two reports on conservation have been received by the Committee. Professor Joseph Kittredge of the University of California summarizes his work as follows: "The project of the California Agricultural Experiment Station on the evolution of the snow-cover under different conditions of forest in the Stanislaus National Forest is being continued for the sixth field-season under a modified plan. It became evident that the ten mechanically spaced stations within a forest-stand were not sufficient for adequate statistical analysis of the wide variation found. Consequently the work is being confined to three of the areas, at each of which the snow at some 30 stations randomly distributed is being measured currently.

"The records of the previous five years are being analyzed. The wide variation in almost all respects between the different areas may be illustrated in Table 6 by the maximum water-equivalent at any one station in each area and the dates on which those maxima occurred in the spring of 1938.

Table 6

Type of cover	Maximum water-equivalent	Date
	inches	
Red fir	51.0	April 8
Mixed conifer (cutover)	37.2	April 7
Open logged area	36.0	March 23
Open screened	32.5	April 6
Sugar pine--Ponderosa pine, mature	29.4	March 23
White fir, mature	27.5	April 6
Ponderosa pine,reproduction	25.0	March 23
White fir, immature	25.0	March 9
Ponderosa pine, mature	21.0	March 25

"The extremes of the maximum water-equivalent are 21.0 inches in ponderosa pine on March 25 and 51.0 inches in red fir on April 8."

Dr. H. G. Wilm and M. H. Collett have prepared a paper for the present annual meeting on "The influence of a lodgepole-pine forest on storage and melting of snow." Their conclusions are as follows:

"Two years' observations of snow-storage in a mature lodgepole-pine forest have resulted in the establishment of the following facts: (1) Canopy-density is an important factor affecting snow-storage and melting in lodgepole-pine stands; (2) slope-percentage, slope-height, and position on the slopes have little or no measurable effect upon volume of stored snow in well-stocked lodgepole-stands; (3) since snow-storage and melt-duration were at a maximum in the largest canopy-openings studied, it would appear that the size of opening providing maximum storage in mature lodgepole-stands has a radius of 30 feet or more."

The conclusions of Wilm and Collett confirm the Chairman's studies of conservation potentiality in the Tahoe forests of pine and fir mixed.

Improvement of equipment

Chatillon and Sons, New York City, have developed a spring-balance possessing a precision estimated at 99.98 per cent and capable of weighing a snow-sampler with snow-core 1-1/2 inches in diameter and 40 feet long. Because of this accuracy it becomes a fair substitute for a springless scale, which is too cumbersome for field-use. This balance can be used also for weighing snow-evaporation pans eight inches deep and 15 inches in diameter, or even somewhat wider. With this instrument the extreme conditions of the Pacific Northwest can probably be met.

Transport

This subject covers both travel and sports.

Snow-removal has been easy the present winter from the highways of the mountainous West where rain fell even in the passes and thus diminished the depth of the snow.

In the middle West rock salt was used to disintegrate ice on the highways.

In the South frost heaved the highways. J. H. Dowling, State Highway Engineer, states that "old roads in North Florida suffered badly in the cold spell. Surface treatment on 518 miles of road that had been down more than five years was so badly damaged that nearly $3,000,000 must be spent at once in order to save the present investment. As Florida operates on a pay-as-you-go basis, finding that amount of money is not easy.

"The damage was confined to the older surface-treated limerock roads, as far south as Tampa; newer roads and the sand-clay roads were not affected. Florida has had as low temperatures before, but has never had as long a period in which one freeze followed another in quick succession. The roads were wet when the first freeze came and the highway engineers think that it opened up the old weak surfacing. The following thaw let the water down into the road where subsequent freezing and thawing continued the disintegration.

"In the reconstruction work, a sand-bituminous mix will be substituted for the surface treatment on part of the work." [V.T.B. Eng. News-Record, March 28, 1940.]

Snow-sports are becoming increasingly popular. Dr. H. I. Baldwin of the Forestry and Recreation Department, State of New Hampshire, writes: "The recreational use of snow for skiing

United States Department of Agriculture
Weather Bureau

WINTER-SPORTS BULLETIN

Issued at Madison, Wisconsin, Great Lakes-Minnesota Area, January 12, 1940

Locality or trail	Weather at 7 a.m. today		Snow		Sports available						Ice	
	Temperature °F	Weather	Average depth (inches)	Description[a] (Example: 2" powder over breakable crust)	Skiing	Tobogganing	Bob-sledding	Skating	Ice-coasting	Ice-fishing	Average thickness (inches)	Condition (S = smooth R = rough H = slushy V = snow-covered)
Wisconsin												
Green Bay	22	Cloudy	2	VN				+	+		7	S
Hefford Junction	22	Hvy Sn	24	SF	+	+	+	+		+	12	S
La Crosse	8	Clear	T	SP				+		+	12	S
Oconomowoc	20	Clear	4	HB	+			+			10	R
Rhinelander	14	Clear	10	SF/HB	+		+	+		+	12	V
Wausau	10	Clear	4	SF				+				
Upper Michigan												
Escanaba	25	Cloudy	5	2" ST/HC	+	+	+	+	+	+	4	RV
Houghton	24	Str Wind	14	1" SP/HB	+	+		+				V
Iron Mountain	19	Lt Snow	12	4" SP/HB	+	+		+			10	S
Ironwood	10	Clear	7	4" SF/HC	+	+	+	+				
Ishpeming	22	Cloudy	14	2" SF/HC	+	+	+	+				
Marquette	27	Cloudy	9	1" ST/HC	+	+	+	+				
Munising	25	Cloudy	14	8" ST/HB	+	+	+	+			6	R
Ontonagon	24	Cloudy			+	+						
Sault Ste. Marie	30	Lt Snow	7	SP	+			+				
Northern Minnesota												
Brainerd	-10	Clear	2	1/2" SF/HB				+		+	20	S
Coleraine	- 8	Clear	6	2" SF/HB	+			+		+	12	V
Duluth	4	Clear	2	SP				+	+		14	S
Grand Marais												
Gunflint Trail	6	Cloudy	7	2" SF/HC	+	Dog teaming				+	18	V
Two Harbors	7	Clear	7	2" SP	+			+		+	18	V
Virginia	6	Cloudy	4		+	+	+	+		+	20	R
Southeastern and Central Minnesota												
Faribault	2	Clear	9	1" SF/HC	+			+	+	+	10	V
Glenwood	24				+	+						
Minneapolis-St. Paul	- 4	Clear	5	2" SP/HC	+	+	+	+	+	+	12	V
Red Wing				SP/HC					+	+		S
Rochester	1	Clear	4	2" SP/HC	+			+		+	5x	S
Shakopee	1	Clear	5	4" SP/HC							14	V
Stillwater	- 2	Clear	7	2" SF/HC	+	+				+	12	V
Taylors Falls	5	Clear	7	SP/HC	+		+	+	+	+	10	R

[a]Abbreviations: S = soft; F = fluffy; P = powder; T = sticky; W = wet; L = slush; H = hard crust; B = breakable; C = common unbreakable; Y = icy unbreakable; D = wind-crust; V = spring conditions; G = granular; N = frozen granular; / = over; X = not reported or unknown

Forecast for Great Lakes-Minnesota Area--Fair, Saturday, except snow possibly in southern Michigan. Mostly cloudy Sunday and Monday, with snow in lower Michigan and southern Wisconsin, and perhaps in upper Michigan and northern Wisconsin. No severe cold likely.

has increased still further in New England and New York. A recent survey by the New Hampshire Planning and Development Commission showed increases of 25 per cent in use of recreational areas and income from business connected with winter sports in New Hampshire. Increase of local manufacture of skis is presaged by the recent prohibition of ski-export by Sweden and threatened similar action by Norway."

Robert G. Stone of Blue Hill Meteorological Observatory has prepared a paper for the annual meeting on "Curves of average snow-cover depth at stations in New York and New England."

Eric R. Miller of the United States Weather Bureau, Madison, Wisconsin, has begun a "Winter-sports bulletin" for the Great Lakes-Minnesota Area. He comments "one sees skis and toboggans tied to the top, or sticking out of the rumble seat of about every other car on the road." The sports bulletin by him on the preceding page is included because of its simplicity and comprehensiveness.

In natural sequence to the influx to the snow-fields is a paper by J. Carlisle Crouch, Chief Ranger, Crater Lake National Park, on "Ski etiquette and ski safety" to be presented at the Seattle Meeting of the Western Interstate Snow-Survey Conference in June, 1940.

The Lassen Volcanic National Park, whose deep snow led to the development of forecasts of snow-sport opportunities in the West, has become the center of the Mount Lassen Midsummer Ski Tournament, held the present year on June 30. The United States Travel Bureau characterizes it as a "unique tournament, held under sunny skies on the snow-blanketed slopes of Lassen Peak."

However, individual peaks from Mount Hood to Mount Baker provide summer opportunities above timber-line to the persistent skier.

Avalanche perils should receive attention, especially by snow-surveyors who traverse high altitudes on schedule and may consequently meet unstable snow. An avalanche unexpectedly destroyed a snow-survey course in the Tahoe Basin the present winter. In the steeper Ruby Range of Nevada, April is a season of snow-slides. In Utah, a party of snow-surveyors was caught by an avalanche and one perished. It was reported that the surveyors went out immediately following a heavy snow which fell upon crusted snow.

The disaster by avalanche on Mount Baker and the report of an "enormous avalanche" on Mount Shasta emphasize the perils of winter mountaineering.

M. H. Davis, Supervisor, Shasta National Forest, comments as follows [Sierra Club Bull., April, 1940]:

"The opinion of some of the people who have seen this slide is that early this winter the first snowfall was wet and heavy and later froze into a very solid and compact sheet of icy snow. Later a very heavy fall of dry powder-snow six to eight feet deep fell on this snow-blanket and this fall of snow was later topped by a layer of wetter snow, forming a heavy blanket on top of the dry snow. It is very possible that falling rocks and debris from either the Red Banks or from the vicinity of Thumb Rock supplied the vibration or jar necessary to start this top layer of heavy snow moving, with the under cushion of dry snow acting as a skidding agent on the bottom layer of frozen snow.

"The main slide was south of the low ridge which in turn is south of the Rest House. Recent storms have added several more feet of snow to the pack on Mount Shasta, but from reports that are available, this last fall of snow is rather wet and heavy and, in the opinion of those with whom we have discussed these slides, there is very little danger of any more avalanches."

Skiing and snow-survey schools are now being held by the Forest Service to provide training for the duties of acting as wardens at winter-sports centers and cooperating in the forecasting of stream-flow.

The motor-sled is meeting an essential need for forest-rangers, snow-surveyors, and for supplementing winter sports. It can be especially valuable for emergency use where the distance is great and further strenuous travel may be necessary at the end of the journey. The Nevada Agricultural Experiment Station has been advising in the perfecting of the Tucker snow motor-sled, which is capable of ascending steep slopes.

On the ocean, Commander Edward H. Smith of the Iceberg Patrol is now developing the forecasts of iceberg-frequency to determine the magnitude of seasonal patrol-service required. It is the purpose of the Ice Patrol, if it has completed its patrol-service sufficiently early in the summer, to make a series of reconnaissance-trips to Cape Farewell and Baffin Bay to observe the accumulation of icebergs on their eventual way to the North Atlantic. His report constitutes a paper at the twenty-first annual meeting of the American Geophysical Union in the series supplementing this report.

Polar regions

Two significant events in polar exploration in the present year are associated with the United States. The first is the Wilkes Centenary of the Exploration of the Antarctic Continent by Lieutenant Wilkes and the second is the third trip by Admiral Byrd, planned originally to

claim sections of Antarctica for the United States, but now becoming chiefly a mapping and scientific expedition.

Two scientific attempts are being made: One at the suggestion of Dr. Charles F. Brooks, Director of Blue Hill Observatory, to catch precipitation in the Antarctic by means of a shielded snow-gage; the other an attempt to traverse broad sections of the ice-fields by means of a self-contained snow-cruiser. The difficulty in achieving the measuring of precipitation is the wildness of the wind, necessitating in Dr. Brooks' opinion the erection of a tower possibly 100 feet high. The possible difficulty with the snow-cruiser is the use of wheels which may bog in the soft snow and in the use of rubber tires which will probably restrict its activity to temperatures above -60° F, at which vulcanized rubber has been found by the National Bureau of Standards to break down.

Dr. Laurence M. Gould, member of the Committee on Snow, has undertaken to provide a map of ice-movement in the Antarctic and thus expand the work performed for many years by the Danish Meteorological Institute through the devotion of Captain Speerschneider.

Many other projects, particularly in ice, were proposed to the Byrd Expedition at the latter's request by the Association for the Study of Snow and Ice of London. This Association consists of many of the leading explorers of the Antarctic.

Scientific polar exploration, 1939 (LAURENCE M. GOULD)

The following summary of polar activity has been provided by Dr. Gould:

The recent activity in Arctic exploration has proceeded during the past year with unabated intensity. Indeed so great and varied has been the activity that a report of this sort can do little more than indicate the expeditions which have carried out work.

Svalbard, Jan Mayen--Norwegian Expedition to Svalbard, 1939; Norwegian Fisheries Expedition to Svalbard, 1939; Mr. Hoel's Expedition to Spitzbergen, 1939; International Geological Expedition to Spitzbergen. The last expedition consisted of members from Sweden, Norway, and Great Britain. Its program was specifically designed for geological work. No reports are yet available as to the extend of work carried out.

Greenland--Professor Ahlmann's Expedition to West Greenland, which is still in the field, has as its primary purpose the study of glaciers on Clavering Island.

The Danish Geological Expedition to Northwestern Greenland, which worked throughout the summer of 1939, devoted its time primarily to geological mapping.

The Saint Andrews West Greenland Expedition, 1939, was composed in part of men who had had previous training in Arctic exploration and was well equipped to do a creditable job in geological research in particular. The Expedition was primarily interested in solving some of the problems concerning Tertiary volcanic activity in West Greenland.

The Danish Thule and Ellesmere Land expeditions, 1939-40, consisted of five men who have been carrying out biological work in the vicinity of Marshall Bay. The plans also call for extensive sledge-journeys in the spring of 1940 for the purpose of collecting geological and zoological specimens.

Russian Arctic Exploration--The principal interest in Soviet Arctic exploration attaches to the drift of the Sedov. The drift of this vessel frozen in the Arctic pack has now been in operation for some two years. The general course has been similar to that followed by the Fram with the exception that the set off has followed a more northerly course and holds the record for the farthest north ever reached by a vessel. Detailed meteorological observations as well as soundings and many other matters of great interest have been continuously under observation by the members of this ship.

Upon the meager knowledge which we have concerning the Sedov it is quite impossible to give a full account of Soviet work in the Arctic because no detailed information has been forthcoming from the Arctic Institute for more than a year.

It appears that additional numbers of new Arctic ports and air-bases are being built and more ice-breakers are being put into commission. Considerable aerial exploration has also been carried out including a remarkable flight covering a total of 6,000 km over the Kara Sea by Vodopyanov.

Iceland--The Cambridge Iceland Expedition was principally concerned with a study of plant and animal ecology.

The primary object of the Cambridge Northwest Iceland Expedition of four men from Cambridge University was ornithological studies which were carried out quite successfully.

Arctic Canada and Labrador--The British Expedition to North Baffin Island, which set out in 1938, completed its work in 1939. Considerable interest attaches to the biological observations made by members of this party.

In addition to these expeditions Captain Robert Bartlett made his usual summer cruise in the Arctic making important collections for various American scientific institutions.

Commander MacMillan likewise made an Arctic voyage to the Canadian Arctic and West Greenland.

A Finnish Expedition to northern Labrador was completed but information about the results is not yet forthcoming.

The Wood-Yukon Expedition under the leadership of Walter A. Wood of the American Geographical Society carried out important and successful aerial photographic map-projects, supplementary to those of 1935 and 1936.

Antarctic regions--The most noteworthy happening in the Antarctic has been the establishment of the United States Antarctic Service and the sponsoring of a Government expedition under the leadership of Admiral Byrd. It is exactly 100 years since the United States sponsored its first Antarctic Expedition under the leadership of Admiral Wilkes. The present United States Expedition has reestablished a post at Little America and one in Palmer Land. Comprehensive programs of scientific activity are being carried out from both of these stations and it is expected that during the field-season of 1940 the two bases will be joined by sledging operations.

The German Antarctic Expedition, which left Hamburg in 1938, returned in the spring of 1939. The work of the Expedition was entirely of a reconnaissance-nature. Considerable photographic mapping was carried out in the coastal regions between longitudes 2° east and 8° to 10° west. German claims in Antarctica were made as a result of this Expedition.

French oceanic work in the Southern Ocean was carried out from the sloop Bougainville. This vessel made regular echo-soundings which are important in confirming and completing in detail those which had been obtained previously.

The most important scientific work carried out through Norwegian sponsorship has been biological investigations on whales. This is a pertinent subject of research on account of the great inroads made in Antarctica by Norwegian whaling activity.

The work carried out by the British paralleled that of the Norwegians in that it was primarily concerned with a study of whales in an attempt to determine the ages of whales.

Publicity

The term publicity for the present report has been enlarged to include not only publications and news but also meetings and organizations.

Bulletins and radio broadcasts have now become the standard method of reaching the public quickly. Bulletins are being issued by reporting organizations where time permits. Reprints of the Western Interstate Snow-Survey Conference and the Report of the Committee on Snow are being purchased by 24 sustaining organizations and distributed to a mailing list of fully 1,500.

Regional meetings in hydrology begun by Dr. Meinzer, early President of the Union's Section of Hydrology, are now in active operation in all of the four western areas of the United States and Canada, namely, North Continental Divide, South Continental Divide, North Pacific Coast, and South Pacific Coast. The Snow-Survey Conference has become an adjunct, though separately organized.

The chief topic discussed at the Stanford session of the Snow-Survey Conference, January 12, 1940, was the relative accuracy of stream-flow forecasting. At the sessions at Seattle scheduled for June, 1940, emphasis will be placed on the study of the optimum conditions for maximum floods and quantitative snow-surveying as conducted mainly in the East where midwinter melting of the snow-cover is prevalent.

The International Commissions of Snow and Glaciers have been united into a single Commission of Snow and Glaciers, comprehending all phases of the study of snow and ice. This Commission thus continues its close relationship with the International Associations of Meteorology and Oceanography as well as with that of Scientific Hydrology. The history of this movement by François E. Matthes has been printed in "Science" [vol. 91, pp. 317-318 (March 29, 1940)] under the title "The new International Commission of Snow and Glaciers." It has also appeared in "Nature" [v. 145, pp. 753-754 (May 11, 1940)]. The officers of the Commission selected, to be confirmed by the Executive Committee of the International Association, are J. E. Church (President), P. L. Mercanton and Hans W:son Ahlmann (Vice-Presidents), and François E. Matthes (Secretary). Thus a close continuity between the American Committees of Snow and Glaciers and the new International Commission of Snow and Glaciers is being maintained.

Emphasis is still being placed upon securing systematic records of the annual variations of the glaciers but will be expanded from America and Europe to cover all other glacier-areas of the world including the Arctic, and particularly the Antarctic.

The movie on snow-surveying in the High Sierra by Los Angeles is now being supplemented by movies of the Central Sierra by Walter J. Herz and Frank W. Wilson of Reno. The former movie is in color. In the northern mountains a voice film on electric power from the snow-fields to the home has been prepared by the Washington Water Power Company of Spokane and another film depicting especially snow-surveying methods in the Cascades will be shown by R. A. Work at the Seattle Meeting.

Through the entnusiasm of Dr. Charles F. Brooks of Blue Hill Observatory, the voice film on the development of snow-crystals in the mountains and laboratory in Japan by Professor Ukitiro Nakaya has now been shown at ten or more meetings in America. This schedule has included particularly meteorological seminars. Professor Nakaya has promised to develop another film showing the future progress of his studies.

The Swiss Avalanche Film presented at the International Meeting at Washington was returned immediately to Switzerland to assure safe return and is now being used in instructing military recruits in avoiding snow-perils in the Alps. This film can be duplicated for 350 Swiss francs, or approximately $78. It should have value in this country because of avalanche-perils that are confronting our snow-mountaineers. Funds are being solicited from various organizations for this purpose.

College instruction is now being given in snow-surveying and the forecasting of stream-flow. The College of Agriculture of the University of Nevada has included lectures in its course in agricultural engineering while the College of Engineering has made field-trips in snow-surveying and actual forecasting an essential part of its course in hydrology. Students from various engineering schools are seeking employment in this field.

A handbook on snow-surveying nas been prepared by James C. Marr, Irrigation Engineer, Division of Irrigation, United States Soil Conservation Service as Miscellaneous Publication No. 380, United States Department of Agriculture. Mr. Marr is Federal coordinator of cooperative snow-surveying in the West.

Research

The three formal questions set by the International Commission of Snow and Glaciers for discussion at its Bergen meeting in 1942 are:

(1) Study of the origin, drift, and dissolution of icebergs, with reference to the forecasting of their seasonal appearance.

(2) Physical changes in the snow-cover conducive to runoff, especially floods.

(3) Study of the crystalline texture of glacier-ice in relation to the mode of movement of glaciers.

Gerald Seligman of England and Dr. Max Demorest of America are active specialists in the last question. A grant has recently been made to Dr. Demorest to continue his study of glacier-crystallization at Yale University.

Other projects latent and active are:

(1) The perfecting of correction-factors for forecasting floods and stream-flow.

(2) The investigation of the critical temperature and density at which snow may suddenly melt.

(3) The cohesion of snow, and avalanche possibility. This includes the study of snow-loads on buildings, particularly where buried deep beneath a continuous snow-cover, as occurs in the Pacific Northwest.

The study of snow-crystals in connection with snow-fields and winter sports is being planned by E. F. Preece, Senior Engineer, National Park Service, in connection with the improvement of the nomenclature of snow. The Soil-Laboratory of the Park Service should provide facilities for the study of its counterpart in frozen water-vapor.

"Starting with a memorandum prepared by the Executive Sub-Committee recommending more comprehensive research in relation to snow-cover, snow-melting, soil-frost, and infiltration through frozen soil, Dr. Nichols has designated W. U. Garstka of the Division of Hydrology, under C. E. Ramser, to take charge of research-work in cryologic hydrology. Arrangements have been made to

establish and maintain a field experiment station for this purpose, in cooperation with the Michigan Agricultural Experiment Station at East Lansing, Michigan," thus reports Robert E. Horton, Chairman of the Research Advisory Committee of the Soil Conservation Service.

Robert G. Stone has urged the establishment of a major snow-laboratory in the West where snow and glacial ice are both deep and abundant.

The Nevada Agricultural Experiment Station in completion of its studies in the evaporation of snow is planning to study in greater detail the evaporation of snow in the crowns of trees.

An aerial relief-map of the Truckee River Watershed, Nevada-California, is being prepared as a section of the Mono National Forest. Such work is fundamental to the study of the advance of the snow-line, which underlies predisposition to floods. It is also essential for the plotting of altitude-zones where contour-maps are not available.

A new project by the Canadian Department of Agriculture is ridging to accumulate snow on fields. This method is being developed in prairie-regions not subject to warm chinook winds and definitely facilitates the growing of vegetables and feed and the control of soil-drifting.

The following are regional reports by members of the Committee:

New England (HENRY I. BALDWIN)

"With the completion of the preliminary flood-control survey of the Merrimack Drainage the Northeastern Forest Experiment Station has transferred its field-headquarters from Concord, New Hampshire, to Greenfield, Massachusetts, and is making a survey of the Connecticut River Drainage. Snow-observations form a large part of the work in winter, and snow-sampling under various types of forest-cover as well as readings at permanent stations are under way. Snow-depth readings have been continued at the Fox Forest in Hillsboro along a course suggested by Dr. Church on his visit last fall.

"New England cities have been troubled by several snow-storms in rapid succession, which created unusually difficult snow-removal problems. Again the vulnerability of modern means of transport compared to those of the horse-and-buggy era was well demonstrated. Snow is thus a Dr. Jekyll and Mr. Hyde--it withholds floods and causes them, it brings joy and health to millions, and blocks roads and streets. Snow is at once the delight and dilemma of New England."

State of Washington (PHIL E. CHURCH)

"The snowfall during this winter has been singular in some respects, especially as to the amount and the time of occurrence. The writer of this report has kept watch on the development of the snow-cover, its depth, settling, and some other characteristics at Snoqualmie Pass, Washington (elevation, 3,019 feet), and, in general, on the snow-distribution in the State. Because I am a beginner in the field of snow and have little or no equipment, the value of this contribution to the report is doubtful.

"Early in the season of snowfall, there appeared to be no signs that anything unusual was in the offing. The first snow occurred in the Pass only a few days after the average date (October 19, 20-year record). The amount of the first snow averaged two inches. October was slightly wetter than average for 9.23 inches of rain fell, total amount of snow was 7.5 inches, but none was on the ground at the end of the month.

"November had but little snow, six inches total, as compared to its 20-year average of 35 inches. None was on the ground on either November 15 or 30. Only three times in the past 20 years has there been less snow during this month. The total precipitation was slightly less than normal--8.20 inches as compared to the average of 10.64 inches. Higher altitudes experienced much the same situation with little snow falling at Mount Baker and Mount Rainier, and Stevens and Cayuse passes.

"By the middle of December, Snoqualmie Pass had a cover of 12 inches (average for that date is 31 inches), which grew in depth to 28 inches by the end of the month (average 48 inches). On this snow had fallen a good deal of rain owing to the continued mild weather. Much of this rain was held imprisoned in the snow and a number of ice crusts developed which prevented loss of some of this moisture. The total precipitation for the month was 19.26 inches compared to an average of 15.71 inches. Higher altitudes received somewhat more snow with the greatest amounts falling at about the 4,000-foot level (example is Stevens Pass). Mount Rainier, at 5,500 feet, had about the same amount as Stevens Pass.

"January again was subnormal in snowfall. Snoqualmie Pass received only 61 inches for the month as compared to a normal of 93 inches. Only once before in the past 20 years has there been less fall there than this year. As a result, there was less on the ground on January 15 and 31 than is usual. The amounts were 37 and 46 inches, respectively, compared to averages of 64 and 79 inches. A number of cold days and nights brought the snow-cover to a temperature below

freezing so that there was little loss by melting. The whole body of snow settled but little except in the top layers. Dye (liquid) spread on top of the snow on January 27 penetrated a layer but six inches in thickness in 14 days. The maximum snowfall during the month occurred between the 4,000- and 5,000-foot level with Stevens Pass and Cayuse Pass having more snow on the ground than Mount Rainier. The amount of melted precipitation at Snoqualmie Pass was only 7.30 inches compared to a normal of 14.07 inches.

"Little snow fell during the first ten days of February, after which considerable fell in three separate storms. At Snoqualmie 109 inches was the total amount for the month compared to the 20-year average of 73 inches. The amount on the ground on February 15 was 64 (average is 90 inches) and on February 29 the depth was 83 inches (average 92 inches). The large amount of snow this month, together with the rain which fell, brought the melted precipitation to 18.08 inches compared to a normal of 10.62 inches. Thus, during the months of October, November, December, January, and February the total precipitation was 62.07 inches compared to the average of 59.63 inches. However, much of this came late during the snow-season on a relatively thin snow-cover. The snow-cover that was formed before the middle of February was quite impervious because of the ice-crusts which were present. Settling of these layers was slow, the major crusts dropping from 20 inches to 15 inches above the ground in two months. Red dye (liquid) sprinkled over the surface on February 9 penetrated a layer 14 inches thick in 12 days, and made no further penetration in the next 16 days.

"Higher altitudes received about the same amount of snow as that at Snoqualmie Pass. As a result, the snow-cover on Mount Rainier and Mount Baker increased in depth, but the amount on the ground was far short of normal. The maximum depth at Rainier came at the end of February with a depth of about 120 inches compared to a normal for that date of 157 inches.

"Snow fell during the first part of March but not enough to materially increase the depth on the ground. On March 8 the greatest depth for the winter was recorded with 87 inches present. This very nearly agrees with the normal of 91 inches on March 15. However, the mild weather had appeared to change the character of the snow for orange dye (liquid) which was sprinkled over the snow-surface on March 9 had penetrated 32 inches in ten days. Orange dye was found in the layer of red dye. Also on March 19 it was found that the red dye now had spread through a layer 21 inches thick. Melt-water from above was distributing the dye through greater thicknesses.

"At higher altitudes warm weather melted and evaporated the snow faster than it accumulated. At the time this report is being written (March 30), Rainier should have 184 inches but has only 115. The same story holds for other high-altitude locations in Washington.

"No water-content measurements have been made, unfortunately. It seems to the writer, however, that the water-content is more nearly normal than the depth of snow-cover. However, the penetration of the dye shows that the snow is rapidly disintegrating and will probably be gone earlier than usual this summer. For early-summer irrigation, however, the amounts should be ample, but not for late-season irrigation.

"The amount of snow this winter was so little that it was possible to keep Stevens Pass open the whole time. This is the first winter that such has been possible. It has been possible also to drive all the way to Paradise Inn all winter, the first time in many years. On the other hand, it has affected the skiing adversely. The number of cars parked at the summit of Snoqualmie Pass is a good indication of the ski population. During the winter season, November through April, the State Patrol counts the cars on Sundays and holidays. During the 1937-38 season there were 15,100 cars, during 1938-39 there were 16,803, and during 1939-40 (through the middle of March) there were but 9,320. The Snoqualmie Ski Bowl, operated by the Milwaukee Railroad, opened later than usual (in January) and closed earlier than usual (in late March)."

British Columbia (R. C. FARROW)

"Table 7 makes a comparison between accumulated precipitation and water-content by snow-sampling on January 31 and February 29.

Table 7

Accumulated precipitation Nov. 1 to Feb. 29			Average depth of water in snow-cover					
			As on Jan. 31			As on Feb. 28 (29)		
At	Inches	Per cent of normal	1940	1939	1938	1940	1939	1938
McCulloch	9.90	98.5	2.5	6.17	6.97	4.4		
Trout Creek	6.77	55.1	2.2	5.75	7.80	3.7		
Field	6.00[a]	74.4	1.8	....	....	6.5	....	6.3
Glacier	19.90	69.2	12.0	....	....	11.0	....	24.5
Canoe River	6.38	107.6				1.3	....	4.3
Revelstoke	18.08	94.2	3.3	....	....	6.2	....	10.0
Farron	17.02	125.8	4.6	....	....	9.6		
Fernie	13.79	73.6	1.7	....	5.0	4.5		
Nelson	13.29	100.7	4.9	....	11.5	8.8		

[a] 7.38 by shielded snow-gage on loan from United States Weather Bureau.

"The loss in water-content is quite apparent from the above tabulation, and it will be noticed that the water-content as on February 29, 1940, was without exception actually less than it had been a month earlier in the two preceding years, that is, on January 31 of 1938 or 1939, 1938 and 1939 being years of approximately normal runoff.

"At most of the points listed the water-content at the end of February approximates 50 per cent of what it normally is at the end of March, so that precipitation in March will have to be abnormally heavy to make up the remaining 50 per cent, and at time of writing it shows no signs of making up the deficit.

"Although the water-content is below normal the percentage of loss based on accumulated snowfall in most cases is, curiously, no higher than usual, even though the loss appears to be due to different causes. The large loss which always seems to occur generally appears to have been through evaporation due to Chinook or Foehn conditions, with little or no accompanying increase in runoff. This winter, however, the loss appears to have been due to almost continuous mild cloudy weather and rain alternating with snow, which has produced intermittent thawing and above-average winter runoff. The humidity has generally been higher than usual, and the evaporation-loss must have been low, else the total loss in water-content would have been much higher than it is.

"Field presents a complete exception to the foregoing: The water-content is just about normal; the difference between accumulated snowfall and water-content on February 29 shows the smallest loss recorded anywhere, and far smaller than in previous years. This appears to have been due to the fact that, while the weather was relatively mild as compared to normal winters, there was very little rain, the snow, however, was wetter than usual; it appears to have been less affected by thawing than in other parts, and the humidity being high there was a minimum of evaporation.

"In the report for the Stanford Meeting (January, 1940), I mentioned that there had been wide discrepancies between forecast and runoff for the Okanagan River in both 1938 and 1939. Studies are now under way to see if lack of precipitation during runoff combined with a Foehn condition of high temperatures and dry winds can be correlated to this discrepancy. An optimum minimum temperature of 50° F has been adopted below which it is assumed there will be no abnormal evaporation. The maximum daily temperatures above 50° F are being tabulated for the period of record for five Okanagan meteorological stations, for the months of April, May, June, and July. The degree-days above 50° F will then be summated for each month. This is, of course, involving much statistical work and the study being incomplete I have no findings to report at this time.

"Density of newly fallen snow at Field, British Columbia--Last year through the cooperation of Merrill Bernard, and with the assistance of Ashton R. Codd, I installed a battery of five United States Weather Bureau shielded snow-gages at Field in the Canadian Rockies (Columbia River Drainage). They came into operation on November 1, 1939, and appear to be working satisfactorily. The results when compared with the records of the ordinary precipitation-station and with snow-sampling are interesting. Three of the gages are actually on the snow-course, and course and gages are within half a mile of the precipitation-station. Total precipitation recorded at precipitation-station November 1 to February 29 was 6.00 inches; that recorded by snow-gages November 1 to February 29 was 7.38 inches; and total water-content in snow-pack was 6.5 inches.

"The precipitation is measured at this station during the winter months in the following manner. Rain is caught and measured in the ordinary rain-gage and recorded as such. After each snowfall, or daily in prolonged storms, the depth of snow is measured in inches on a flat platform, and then the platform is swept clean; the depth of snow is recorded and this is divided by ten to obtain the water-equivalent.

"The shielded snow-gages recorded 1.38 inches more precipitation than the precipitation-station did. The latter is evidently in error since the water-content by snow-sampling was 0.5 inches more than the recorded snowfall. The method of measurement may well introduce some personal error, but it is probable that most of the error is through the assumption of ten per cent density for the newly fallen snow. My observer at Field commented on the wetness of the snow.

"The precipitation as recorded by the depth-method and by the shielded snow-gages compare as in Table 8.

Table 8

Date	Gage	Inches of water	
		By depth-measurement	By snow-gage
Nov. 1, 1939	Rain	0.34	0.34
Feb.29, 1940	Snow-depth 56.6 inches	5.66	7.04
	Total	6.00	7.38

Therefore the density of the snow appears to have been
(7.04 × 100)/56.6 = 12.5 per cent

Summaries of leading publications

Since interest is centered at present in the physics of snow, a summary of "Der Schnee und Seine Metamorphose" by Swiss scientists is presented by its authors in English preliminary to the complete translation now under way. This work is the latest and most complete treatise on the subject.

In the Transactions of the Western Interstate Snow-Survey Conference at Stanford [Trans. Amer. Geophys. Union, 1940], a complete transcript was published of the spoken part of the film by Professor Ukitiro Nakaya on "Formation of snow-crystals in the mountains and in the laboratory in Japan."

Summary of "Der Schnee und Seine Metamorphose"

von H. Bader, R. Haefeli, E. Bucher, J. Neher, O. Eckel,
Chr. Thams mit einer Einführung von P. Niggli

The volume is divided into five sections, namely: (1) Meteorologische strukturelle Charakterisierung der Schnee und seine Metamorphose; (2) Schneemechanik; (3) das Zeitprofil und eine graphische Darstellung der Entwickelung der Schneedecke; (4) Schneeuntersuchungen im Gelände; (5) Untersuchungen über Dichte, Temperatur und Strahlungsverhältnisse der Schneedecke in Davos. The following themes presented at the Washington Meeting of the International Commission of Snow have been selected for summary:

Changes in snow during and after deposition by P. Niggli--At the Weissfluhjoch Station of the Swiss Commission for Snow and Avalanche Research further endeavors have been made to characterize snow as an ever-changing aggregate of crystals. On the state of this aggregate depend all the technically important properties of snow. The research-station was situated at a height of about 2,700 meters, so that the winter snow-cover remained dry during most of the winter season. To start with, studies were made in the laboratory on the change undergone by skeletal snow-crystals when the temperature is held constant and air is excluded. A complete remodeling of the material takes place, involving reduction of surface, simplification of shape, and the disappearance of all points. Under the influence of wind the changes take place during the fall of the snow and in any case occur in nature very soon after its deposition. This process of metamorphism continues in the highly porous snow aggregate during settling and after the superposition of furtner snow-layers. The air in the snow-layer is, on an average, saturated with water-vapor. Currents of air and differences in temperature between the lower layers and the surface tend to accelerate the changes. After a certain time a characteristic distribution of the grain-sizes is achieved which can be ascertained by sieve-analysis. At the same time the density, porosity, and permeability to air were determined and these various values coordinated with the firmness. From the results obtained a classification of snow-deposits has been worked out, the usefulness of which is to be tested during the coming winters at various points in the Swiss Alps.

Extensive experiments were undertaken to determine the influence of temperature on the rate of recrystallization within the snow-cover. A decrease of temperature from -2°2 C to -17°5 C reduced the rate of recrystallization by about one-half. (The vapor-tension at -17°5 C is about one-quarter of that at -2°2 C.)

For the purpose of studying the structures and textures of snow-deposits a method of making thin sections was worked out. To effect this all pores had carefully to be filled up. Tetrabromethane proved to be well adapted for this purpose, having a melting point of 0°1 C, while readily lending itself to under-cooling down to -10° C. It is insoluble in water, wets the ice, and freezes without any marked change of volume to an aggregate of fine needles which cannot be confused with ice under the microscope. The pores are filled at between -3° C and -10° C. A snow-layer of a density greater than 0.25 is generally sufficiently stable to be filled without damage to its structure. After the solidification of the liquid thin and polished sections can be made for microscopic examination.

Particular interest attached to the question whether any regulation of the fabric arises as a result of natural and artificial mechanical straining. This is actually the case and the shearing tendency (plasticity) of ice-crystals after the basal plane was distinctly noticeable. The effects are similar to those shown by the hexagonal metals. The effect of temperature on the shearing was distinct.

All snow-samples collected on the test-fields and subjected to mechanical deformation were examined from these crystallographic points of view and in respect to their fabric. The technical properties of the snow proved definitely to depend on the degree of metamorphism in the snow-cover. It is, therefore, essential to complete every examination of snow by giving a mineralogical definition of the particular variety of snow concerned.

In the field, detailed observations were made on profiles of various exposures to study the influence of local effects of weather and ground on the process of snow-metamorphism. On north slopes the lower layers are usually completely altered to depth-hoar. Profiles on southern slopes showed the formation of Sun-crust and the alteration of the inhomogeneous parts. Considerable importance attaches on some slopes to the circulation of air in the snow-cover. This was made evident by the infiltration of gas (acetylene). It seems possible, according to these experiments, that the snow-air after being warmed by the ground on the steep slopes moves upnill along the layers. No marked currents could be detected perpendicular to a pronounced stratification. Air-circulation is of especial importance after fresh falls of snow. When cold snow is sedimented onto warmer snow, the warm air immediately rises into the former. If the new snow is compact an air-current is produced along the dividing layer and leads to recrystallization. If the new snow is loose an accelerated metamorphism takes place in its own lower layers.

The research-work was largely carried out by Dr. H. Bader (mineralogist) and J. Neher (geologist) and their assistants. It is being continued with the cooperation of Dr. R. U. Winterhalter for the purpose of obtaining a clearer insight into the formation of firn-snow. The first results of these investigations on the alpine winter snow-cover are contained in a book "Der Schnee und seine Metamorphose" recently published by the Geotechnical Commission of the Swiss Society for Research in Natural Science (Schweizerische Naturforschende Gesellschaft) and the Swiss Society for Snow and Avalanche Research.

Snow-mechanics by R. Haefeli--The changes or metamorphism of snow are intimately connected with the action of external mechanical efforts, on the one hand, and, on the other, with climatic conditions. In order to study the effects of the various factors in their natural coordination, both laboratory- and field-investigations were so carried out as to be mutually complementary.

(1) Laboratory experiments--With the aid of specially constructed apparatus, investigations were carried out on the following properties of snow: Unit-weight, porosity; permeability to air; compressibility by free lateral expansion; plastic dilatation under tension (Dehnbarkeit); creeping under shearing forces (Schiebbarkeit); compression strength; tensile strength; shearing resistance and cohesion.

It is characteristic of the great variability in the composition of snow that the values found to express each of the above-mentioned properties varied within limits of 1:100 and more. For the rapid characterization of the snow-varieties those determinations are especially valuable which can be carried out quickly and without noticeably changing the structure of the snow. These are especially the determination of the unit-weight, permeability to air, and the tensile strength. The permeability to air is expressed in a similar fashion as the permeability to water of detrital rocks, by the coefficient of permeability k (that is, the rate of filtering of air under a pressure-gradient J = 1). The value of k varies between the limits of about 40 cm/sec (wind-packed, fine-grained snow) and 1,000 cm/sec (coarse-grained, non-cohering, old snow). The tensile strength can be determined fairly accurately by means of a centrifuge-apparatus and shows values up to 220 kg/dm^2 (2.2 kg/cm^2) for wind-packed, fine-grained snow. The investigation of the plastic behavior of snow, that is, of the processes of creeping (compressibility, plastic dilatation under tension, creeping under shearing forces) under varying mechanical efforts is another indispensable foundation for the elucidation of the strain-phenomena in the natural snow-cover which may enter into a critical stage and lead to avalanche formation. Of especial importance is the establishment of the fact that the mechanical behavior of snow is in many respects related to that of a viscous though not volumetrically constant liquid.

(2) Field experiments--The work done included (inter alia) the following: The construction of a complete time-profile for the snow-cover; profile-taking on slopes of various exposure; investigations on avalanches; measurements of snow-pressure.

The time-profile which comprises observations taken weekly in a horizontal test-field is in principle a graphical rendering of the properties of the snow-cover and the meteorological medium in function of time. By plotting the profiles against a time-axis, the metamorphism of the snow-cover, or rather of the various layers, is made clear. The time-profile thus enables the many individual results obtained during a prolonged period of investigation to be coordinated and compared. As to the basis of all comparative investigations of the natural snow-cover, it also facilitates the development of avalanche-prognosis. The following processes in and properties of the snow-cover on Weissfluhjoch, winter 1936-37, are represented: Settling; permeability to air; temperature; resistance to ramming; cohesion; and melt-water. As the metamorphism is largely governed by the meteorological conditions, wind, temperature, and radiation were also plotted against a time-axis.

During the investigation of the natural snow-cover in the horizontal test-field (time-profile), on various exposed slopes and the scars of avalanches, the taking of "ram-profiles" proved particularly instructive. By resistance to ramming we mean the resistance in kg which the natural snow-cover offers to a conical metal point of given dimensions when rammed in vertically For its determination a simple instrument (a sounding rod) was used. If the resistances to ramming be plotted as abscissae in function of the total depth of penetration, a "ram-profile" is obtained which offers an instructive picture of the various degrees of firmness in the different snow-layers.

Exhaustive tests were made on wind-slab avalanches, the most frequent and dangerous type of avalanche in the Alps. From the standpoint of snow-mechanics the term wind-slab avalanche should be given a more general definition. The essential features of this type of avalanche are the following: (a) The slab-like stiffening of the sliding layers; (b) the muffled or sharp cracking sound which accompanies the formation of fissures (that is, the overcoming of tensile forces in the zone of tension); and (c) the breaking up of the moving snow into large blocks. A further essential is the presence of a marked surface of discontinuity or of an intermediate layer of extremely low cohesion and low shearing strength (glide-layer).

The nature and origin of the glide-layers can be very different. In mid-winter, that is, in the absence of water-lubricated glide-layers, three types of discontinuity-planes can be distinguished due principally to progressing metamorphism. The first type comprises those wind-slab avalanches which go down during or shortly after a fall of new snow on a crusted surface. In this case the glide-layer is generally formed by a loose inter-layer resting immediately on the crusted surface. The layer is often hardly discernible and merges almost without transition into the wind-packed new snow. The formation of the loose inter-layer is often aided by the fact that the wind only sets in after the snowfall has begun. In this case the glide-layer is largely identical with the old crusted surface which undergoes dry lubrication by the glide-layer. As soon as the crusted layer is covered by new snow its metamorphism takes another course. A break-down of the grain-structure takes place which in the course of hours or days robs the crusted layer of most of its cohesion and gives it the character of a lubricating layer. This produces a second type of discontinuity which may be responsible for the formation of those wind-slab avalanches which are particularly dangerous as they involve very large masses of gliding snow. The continued loosening of the crusted layers is sometimes furthered by the formation of depth-hoar, a completely metamorphosed type of snow. This process leads to a third type of critical discontinuity in which certain snow-layers (as a whole or in part) or even large layer-complexes become transformed into more or less incoherent depth-hoar. This metamorphism usually starts near the ground, but can extend over whole layers or even the whole snow-cover.

Creeping movements were measured on the surface of the snow, within single layers and along a vertical line through the snow-cover. These observations are closely related to the study of strain-phenomena in the snow-cover and of avalanche-formation on the one hand and, on the other, to the measurement of the pressures excited by an inclined snow-cover on rigid supports. These pressure-measurements carried out on smaller and larger elements as well as on continuous avalanche-walls offer an important starting point for further developments in the technique of counter-avalanche defenses. At the same time the pressure-measurements permit the control of theories developed in the strain-phenomena.

(3) Practical applications--The developments of the methodical side of the investigation claimed several years' work, so the practical applications are as yet still in the initial stages. Positive results have, nevertheless, been obtained in various directions.

In Switzerland weekly forecasts of the snow-conditions and the danger of avalanches have latterly been published in the press and on the radio by the Swiss Skiing Association. The Weissfluhjoch Station of the Swiss Commission for Snow and Avalanche Research has actively co-operated in working out these forecasts. In this connection the time-profile as well as systematic observations on avalanches have been found to furnish valuable data.

On Alp Grüm we have cooperated with the Director of the Bernina Railway in tackling the practical problems of counter-avalanche defenses. The study of snow-mechanics and of strain-phenomena in the snow-cover and the measurements of snow-pressure have in many cases led to a new system of construction offering considerable economic advantages.

Some of the methods developed for the investigation of snow-mechanics have tentatively been applied to the study of ice. The results obtained indicate the usefulness of these methods of glacier-research. The connection between snow- and soil-mechanics, although in some cases amounting to diametrical opposition, has produced many useful suggestions for further research in the latter field.

The investigations on snow-mechanics described were carried out by the Department of Soil Mechanics in the Research Institute for Hydraulic Engineering at the Swiss Federal Institute of Technology at Zürich. They were undertaken at the instance and under the auspices of the Swiss Commission for Snow and Avalance Research. The author was assisted by E. Bucher and Schwab.

Honors

At least partly because of his organization of the Federal Forecast Service of Snow Water Supplies, Walter W. McLaughlin, Chief of the Division of Irrigation, now a part of the Soil Conservation Service, will receive the John B. Deere Medal bestowed upon those who have performed the greatest service in the advancement of agriculture during the year.

Death

Tribute should be paid to the memory of Benjamin C. Kadel, a pioneer in the study of the

conservation of snow at Wagon Wheel Gap Experiment Station and for a quarter of a century in charge of the Instrument Division of the United States Weather Bureau. He was inventor of the large-diameter Kadel snow-sampler developed to obtain more accurate cores of coarse-granule (tapioca) snow.

Appreciation

Appreciation particularly is expressed by the Committee to the Nevada Agricultural Experiment Station that has provided clerical assistance, and to the various organizations that have cooperated so fully in making it a center of guidance. It is hoped soon that the direction of the Committee can be taken over by others who are now entering fully into its possibilities.

[For list of current publications on snow and ice prepared by Carl Elges, see addendum to these Transactions, pp. 750 and following.]

Nevada Agricultural Experiment Station,
Reno, Nevada,
April 30, 1940

COMMITTEE ON GLACIERS, 1939-40

François E. Matthes, Chairman

(Published with the approval of the Director of the Geological Survey)

The Committee on Glaciers is now composed of the following members: Harry Fielding Reid, Professor Emeritus of Geology, Johns Hopkins University, 808 Cathedral Street, Baltimore, Maryland; William H. Hobbs, Professor Emeritus of Geology, University of Michigan, Ann Arbor, Michigan; Lawrence Martin, Chief of the Division of Maps, Library of Congress, Washington, D. C.; J. E. Church, Professor of Meteorology, Agricultural Experiment Station, University of Nevada, Reno, Nevada; Wm. Osgood Field, Jr., Explorer, 18 West Twelfth Street, New York, N.Y.; Earl A. Trager, Chief of the Naturalist Division, National Park Service, Washington, D. C.; Oliver Kehrlein, Chairman, Committee on Glacier Studies, 1050 Mills Tower, 220 Bush Street, San Francisco, California; Kenneth N. Phillips, Associate Hydraulic Engineer, Water Resources Branch, United States Geological Survey, Chairman, Research Committee of the Mazamas, 806 Post-Office Building, Portland, Oregon; William S. Cooper, Professor of Botany, University of Minnesota, Minneapolis, Minnesota; Gerald FitzGerald, Senior Topographic Engineer, Alaska Branch, United States Geological Survey, Washington, D. C.; Lawrence M. Gould, Professor of Geology, Carleton College, Northfield, Minnesota; François E. Matthes (Chairman), Senior Geologist, Section of Glacial Geology, United States Geological Survey, Washington, D. C.

The international relations of the Committee have changed somewhat during the past year as a result of the consolidation of the International Commission of Glaciers with the International Commission of Snow. That consolidation was effected by the International Association of Scientific Hydrology (to which both commissions belonged) at the triennial meeting in Washington, in September, 1939. Inasmuch as the membership of the new International Commission of Snow and Glaciers comprises the personnel of the two former commissions, our Committee on Glaciers now automatically is represented on the new International Commission by four men--Church, Hobbs, Gould, and Matthes. Moreover, Church is acting President, and it is understood that he will become President as soon as the political situation in Europe permits the holding of a formal election of officers at which all nations interested can exercise their right of voting.

In the organization of the new International Commission of Snow and Glaciers provision has been made for a permanent Committee on Glacier-Measurements and Research which will carry on the work in which the old International Commission of Glaciers was chiefly engaged--namely, that of securing systematic records of the variations in length and volume of existing glaciers in response to fluctuations of climate. On that Committee, which is to work on a world-wide scale, embracing in its scope all of the great glacier-districts of the different continents, our American Committee will be represented by two men--by Gould, whose special province will be Antarctica, and by Matthes, who will cover the North American field. Thus, it will be seen, an intimate bond has been established between our Committee and the new International Commission of Snow and Glaciers--a bond that will operate to their mutual advantage.

Aside from this far-flung enterprise the Commission has planned for the triennial ending in 1942 the following formal program:

Question 1--Study of the origin, drift, and dissolution of icebergs, with reference to the forecasting of their seasonal appearance.

Question 2--Physical changes in the snow-cover conducive to runoff, especially floods.

Question 3--Study of the crystalline texture of glacier-ice in relation to the mode of movement of glaciers.

In addition the following four special projects have been assigned to temporary committees:

(1) Standardization of maps of snow-cover and ice-cover for the world.

(2) Uniform classification of different types of snow and snow-cover, and uniform nomenclature for the same.

(3) A system of classification for the international bibliography of snow and ice.

(4) Standardization of methods of snow-surveying and forecasting runoff from snow.

All of these new organizational developments and the broadened scope of international glacier-research which they have in view are part and parcel of the remarkable wave of advance in glaciologic science that has been gathering momentum during the past few years. In this advance the United States has been taking an active part. To make more clear the nature and the significance of the contributions that were made by Americans in 1939, it will be appropriate first to state briefly along what lines glaciologic research is making particularly rapid headway at the present time.

First, by securing quantitative measures of the different elements that are involved in the material economy of a glacier, that is, quantitative measures of the annual accretions of new snow in the upper parts of a glacier, of the thicknesses of névé that are thus added to the ice-mass from year to year, and likewise of the volumes of ice that are annually lost by melting and evaporation from different parts of a glacier.

Second, by the application of the methods of optical crystallography to the study of the texture of névé and of glacier-ice, respectively, for the purpose of ascertaining the process whereby the former is transformed into the latter, and of determining how the mass of a glacier yields to the deforming stresses that arise from its characteristic gravitational movement.

Third, by intensive search for data, geomorphologic, climatologic, biologic, archaeologic, and other, that may throw light on the history of glacier-variations during the Post-Pleistocene interval.

The first line of research, of which Ahlmann, of Stockholm, is today the chief exponent, has not yet been essayed in the United States. It necessarily demands a prolonged sojourn by the observers on the surface of the glacier or in its immediate vicinity; and it involves the digging of pits and the sinking of shafts in the ice, as well as the measuring of ablation under recorded weather-conditions [see 1, 2, 3 of "References" at end of report]. It is much to be hoped that investigations of this type will be undertaken in the near future on some of the larger American glaciers, for, although laborious, they unquestionably furnish at last a reliable factual basis for our conceptions of the material economy of glaciers.

The second line of research, by the application of the technique of optical crystallography to the texture of névé and of glacier-ice, was first undertaken in 1938 by a party of English scientists under the leadership of Gerald Seligman. This party did its work in a low-temperature field-laboratory hewn in the practically stationary ice that clings to the rock-slope above the bergschrund of the great Aletsch Glacier, near the Jungfraujoch, in Switzerland, at an altitude of over 11,000 feet. Although necessarily to be regarded as a pioneer attempt with a totally new, untried method of attack, this piece of research by the Jungfraujoch-party, as it has come to be called, has proved eminently successful and has yielded important results. It has served to give us a better insight into the manner in which fine-grained, loose-textured névé is transformed into solid, coarsly crystalline glacier-ice than could previously have been obtained by microscopic methods of observation; it has definitely established the fact that under differential stresses both névé and glacier-ice undergo progressive plastic deformation, each in its own way; and that such plastic deformation, or flowage, takes place even in the lower portion of the glacier-tongue, which is most subject to shearing movements; and, finally, it has shed light on the rôle played by percolating melt-water, both in consolidation of the névé and in raising its temperature in summer from the winter-low [4, 5, 6].

Of these different findings most important, unquestionably, are the direct proofs obtained of plastic flowage under differential stress; for thus far demonstration of the actuality of such flowage has rested on indirect evidence only, such as the curvature of grooves and striae

around the irregularities in a glacier-bed. By some geologists such testimony has been regarded as inconclusive. The researches of the Jungfraujoch-party afford splendid confirmation of the inferences as regards the flowage of glacier-ice which Max Demorest [7] has recently drawn from his observations on smoothly curving, sinuous striae revealing deflection of the ice around obstructions and among the varied irregularities in its path, in precisely the same manner in which a viscous fluid would be deflected. Glacier-ice, he felt justified in concluding, under sufficient pressure obeys the laws of fluid mechanics.

In the United States also a beginning has recently been made in the application of the crystallographer's technique to the study of glacier-ice. During the summer of 1939 Demorest established high up on the flank of Mount Rainier a field-laboratory in which specimens of ice from different parts of adjacent glaciers could be cut and examined under the microscope. In addition he succeeded in shipping selected blocks of glacier-ice across the breadth of the country to New Haven, Connecticut, where in a low-temperature laboratory he has since studied their behavior when subjected to differential stresses. A special pressure-apparatus was designed for the purpose. The deformations produced are recorded on motion-film, and the reorientation of the individual ice-crystals with respect to the direction of stress is observed through a specialized ice-study microscope. Thus the intimate details of ice-flowage are being studied by the methods of petrofabric analysis, which were devised originally for the study of crystalline rocks.

Although these new investigations may seem to be of interest chiefly to the physicist and the student of glacier-mechanics, they are important also to the hydrologist. For the hydrology of glaciers is something more than merely a matter of recording variations of runoff. Fundamentally it is concerned with the material economy of glaciers--that is, with the balance between income of new snow in the upper portions and outgo by melting and evaporation in the lower portions, and this balance is made possible only by the gravitational movement of the glaciers. The snow that annually accumulates in the frigid upper zone is slowly transferred in more and more compacted form to lower levels, where, as a result of greater warmth, it is dissipated in the form of water and water-vapor. The hydrologist, therefore, like the geologist, will benefit by this new line of research initiated by Seligman and Demorest, and as a result of it doubtless will eventually be able to clarify his mind in regard to the basic facts of glacier-structure, glacier-motion, and glacier-economy, which hitherto have remained largely in the realm of conjecture and controversy.

In the third field of glaciologic research--that dealing with the variations in size of existing glaciers in response to climatic fluctuations--the principal advances in 1939 were made, so far as can be ascertained from the information at hand, in the United States and by members of this Committee. Data were obtained that set on a firmer basis than before the tentative conclusions announced in the Committee's report of April 1939 [8], to the effect that:

(1) The present cirque-glaciers on the Sierra Nevada of California represent a new generation of ice-bodies of late Post-Pleistocene origin, at most 4,000 years old, and not dwindling remnants of the great ice-streams of the Pleistocene epoch. They occupy the cirques that were left empty by the complete extinction of their Pleistocene predecessors during the warm and dry middle portion of the Post-Pleistocene interval.

(2) The majority, perhaps all, of the cirque-glaciers and tiny glacierets that exist today on the other mountain ranges in the western United States by inference belong to the same new generation.

(3) The larger glaciers in northern Washington, in Canada, and in Alaska presumably did not melt away entirely during the warm middle third of the Post-Pleistocene interval but were greatly reduced in size. They have reexpanded since then to the limits from which they are even now receding, and as their reexpansion has been of considerable magnitude, to judge from certain specific cases, there appears to be warrant for the assertion that the present age is witnessing a mild recrudescence of glacial conditions--that it is, as a clever journalist has suggested, a separate "little ice-age."

Those tentative conclusions were based, in the first instance, on the numerous observations which the Chairman of this Committee has made during past years on the youthful moraines that lie at the fronts of existing cirque-glaciers in the Sierra Nevada, in the Cascade Mountains, and in various ranges of the Rocky Mountain System. In addition, substantial confirmation was found in 1938 in the Post-Pleistocene history of Owens Lake, as reinterpreted by Antevs [9], and, what is more, from that history a rough measure was obtained of the age of the present Sierra glaciers and therefore, also, of the total duration, thus far, of the "little ice-age."

During 1939 both the evidence from the moraines and the confirmatory proofs from Owens Lake were materially strengthened by further observations. As these evidences are primarily geomor-

phologic a full presentation of them would hardly be appropriate in a report of this Committee, yet, inasmuch as they afford us an entirely new perspective of the sequence of glacial events during the Post-Pleistocene interval, and give us a juster conception of the relation which our "little ice-age" bears to the great Pleistocene ice-age, it seems appropriate that they should at least be briefly sketched.

First, as to the moraines that lie at the fronts of the existing cirque-glaciers. Those moraines have three notable characteristics:

(1) They have a strikingly raw, unweathered, new-made appearance that contrasts with the more-settled, weathered, and subdued aspect of even the youngest recessional moraines of the last Pleistocene glaciation that lie in the canyons below.

(2) They are isolated, as a rule, from the youngest Pleistocene moraines by a long stretch of canyon that is essentially unencumbered by morainal accumulations. Nor is there anything resembling a gradational series of successively younger deposits leading up to them from the Pleistocene moraines.

(3) They consist as a rule of one massive compound embankment, next to the glacier, and several lesser, concentric outer ridges. Though low and small as compared with the great moraines of the Pleistocene glaciers, the compound embankments are surprisingly high and bulky for the small cirque-glaciers by which they were formed.

The characteristics noted under (1) indicate, of course, an extremely recent origin for the moraines in question. The Chairman of this Committee has long been of the opinion that they are comparable with the "modern" moraines in the Swiss and French Alps, whose dates of deposition, it is definitely known from authentic documentary records, fall within the periods of 1818-20 and 1850-55. The small outer moraines of the Sierra glaciers date probably from earlier centuries. The absence in the upper canyons of a gradational series of progressively younger moraines leading up to the modern moraines at the glacier-fronts would seem to indicate that towards the last the Pleistocene glaciers receded steadily, rapidly, and without halts or readvances. Their retreat doubtless was accelerated by the progressive warming up of the climate, just as was the retreat of the continental ice-sheet in eastern North America and that of Scandinavia. And as the Sierra Nevada lies far out on the southern fringe of the glaciated portion of the Continent, it is a fair presumption that its ancient glaciers continued to melt back rapidly until nothing was left of them.

The disproportionately large size of the moraines at the fronts of the Sierra glaciers, which to all observers has seemed difficult to account for, suddenly stood explained last summer, as the result of a fortuitous occurrence at the front of the Conness Glacier, which is situated just beyond the eastern boundary of Yosemite National Park. Between the rapidly wasting front of that Glacier and the massive morainal embankment that encircles it a lake was formed, and the waters finally rose to the level of a sag in the crest of that 100-foot ridge and began to pour over. In less than ten days the lake was drained completely and it was found that the waters had cut a narrow slot-like gash in the embankment. The vertical walls of that gash turned out to be composed of solid, stratified glacier-ice, and the coarse rock-débris that gives the embankment the aspect of a moraine was found to form merely a thin veneer on the ice-core. It constitutes but a small fraction of the total bulk of the embankment, and it was apparent that ultimately, when the ice-core has melted away, the embankment, now so imposing, will be reduced to a relatively low, insignificant moraine similar to the small concentric ridges that lie outside of it.

The embankment of the Conness Glacier being typical of its kind, it may properly be inferred that all analogous embankments at the front of other Sierra glaciers likewise consist of ice-cores mantled with rock-débris. Those ice-cores doubtless are residual portions of the glaciers themselves and date from the time of the last great advance. They have been preserved by the mantling rock-débris, which acts as an effective insulator and protects them from the heat of the Sun and the air. The cleaner ice farther back on the Glacier, on the other hand, has wasted away for lack of such protection.

The discovery of the ice-core in the Conness moraine, it need hardly be added, establishes beyond possible doubt the extreme youth of these embankments. Although little is known about the length of time that a mass of "dead ice" (Todteis, it is aptly termed by European glaciologists) such as that at the Conness Glacier can persist under its protective covering, it seems likely in any event, both from its great height--80 to 100 feet--and from the thinness of its débris-mantle--five feet or less on an average--that its age is to be measured in decades rather than in centuries. For, though the rock-débris is a good insulator, it is not a perfect one, and doubtless allows a slight amount of heat to penetrate through it every summer, causing the ice

underneath to melt a trifle. Thus the embankments are being reduced very gradually in height and in bulk at progressively slower rates as the protective mantle thickens by the addition to it of further rock-débris released from the ice. Moreover, they are also being undermined in places by melt-water from the glacier, as is evident from the cave-ins that were observed in 1936 at the front of the Maclure Glacier, in Yosemite National Park, and in 1938 at the front of the Palisade Glacier, farther south in the Sierra Nevada.

That the great morainal embankments of the Sierra glaciers were in existence in the early 1880's, in much the same form as now, is clear from I. C. Russell's writings [10, 11]. The date of their origin, therefore, lies farther back. If there is any close synchronism between the glacier-oscillations in the western United States and those in Europe, it may well be that the embankments of the Sierra glaciers correlate with the historic advance of 1850-55, which is definitely on record in the Alps, in Scandinavia, and in Iceland. They may, of course, correlate with the advance of 1818-20, which was of about the same magnitude, or they may represent the combined products of both advances, but it seems improbable that they date back to the eighteenth century or to the seventeenth, which also were times of notable glacier-expansion in the Old World. The small outer moraines of the Sierra glaciers very probably date from those earlier centuries.

Whether or no any close synchronism actually exists between individual glacier-maxima of short duration (small peaks on a curve of long-time swings) in the Old World and the New, this much can be asserted with some confidence on the strength of the data now at hand, that throughout the last three centuries the glaciers in Europe and in the western United States were appreciably larger than during the preceding centuries, and their maxima in the seventeenth, eighteenth, and nineteenth centuries were without a doubt the greatest ice-extensions that have occurred since the end of the Pleistocene ice-age.

It may well be added, lest there remain any misapprehension on that score, that the rapid decline of the glaciers that is now being witnessed in the United States and in Europe does not necessarily mark the end of this recent period of glacier-expansion. It may be only a temporary recession--one more of the many temporary recessions that have occurred during the last 300 years and that are at least partially recorded by the intervals between the successive moraine-ridges so beautifully developed at the fronts of some of the Sierra glaciers. It is significant in any event that in spite of their recent recession the Swiss and French glaciers today are still much longer than they were during the Middle Ages. The sites of the villages that were overwhelmed by them during the catastrophic advance of 1643-44 are still under the ice [12].

As regards Antevs' tentative interpretation of the Post-Pleistocene history of Owens Lake, which furnishes an important clue to the probable age of the present Sierra glaciers and thereby also to the duration, thus far, of the "little ice-age," it was deemed desirable that it be checked, if possible, by first-hand examination of the field-facts. Accordingly, the Chairman of this Committee last summer undertook to make such an examination in the few days at his disposal in connection with the geologic studies he was carrying on along the east front of the Sierra Nevada. The specific facts to be established will appear from the following synopsis of Antevs' thesis [9]:

Accepting Gale's [13] figure of a round 4,000 years for the time that was required for the accumulation of the salt now contained in Owens Lake, Antevs reasoned that in all probability that accumulation dated, not from the time when the waters ceased to overflow, as Gale supposed, but from the time of the birth of the present lake itself as a new pool in the dessicated basin of the much larger and deeper lake that occupied Owens Valley during glacial times. That ancient body of water, he contended, must have dried up completely during the warm and dry middle third of the Post-Pleistocene interval, and the present lake was formed in consequence of the return of somewhat cooler and moister conditions during the last third. He postulated, further, that the present lake, like other saline desert lakes of its class in the Great Basin, had not inherited any of the salt left from its Pleistocene predecessor, the salt having been in part buried under alluvial and eolian deposits, in part blown away by the wind, during the prolonged period of dessication. The present salt-content of the lake therefore affords a rough index of its age.

Owens Lake, being situated at the east base of the Sierra Nevada, in an arid region that receives but scant precipitation, depends for its sustenance very largely upon the runoff from the heavy snows that mantle the range in winter. It therefore seemed to the Chairman of this Committee a proper inference that the history of the extinction and subsequent rebirth of the lake during Post-Pleistocene times might well indicate a closely parallel history for the glaciers on the range. Knowing how delicately adjusted the present small ice-bodies are to the prevailing climatic conditions, it seemed to him extremely unlikely that they could have survived

a prolonged xerothermic period. He therefore felt justified in concluding that they, like the present lake, are products of the relatively cool and moist conditions of the last third of the Post-Pleistocene interval. The same conditions of snow-precipitation and of temperature that brought back the lake also brought back the glaciers, and the latter accordingly are, in round numbers, 4,000 years old.

The critical facts to be verified, then, are, first, that the Pleistocene Owens Lake dried up completely during the warm middle third of the Post-Pleistocene interval, and, second, that the salt which it left behind was not inherited by the modern Owens Lake. Observations therefore were made on the conditions that govern alluviation in the lake-basin at the present time, and the logs of deep wells driven in the immediate vicinity of the lake were secured in order to ascertain from the character of the sediments the nature of the conditions under which they were laid down. The facts found may be summarized as follows:

(1) The Owens Lake Basin is today, and doubtless has always been, an area of fairly rapid alluviation. It is so by reason of its location between lofty mountain ranges whose steep flanks are but sparsely covered with vegetation, and from which the waters from melting snow as well as from occasional thunderstorms ordinarily run off in torrential fashion.

(2) The full effect of alluviation, especially at the foot of the Sierra Nevada, is not readily apparent because of the progressive subsidence of the Basin at its western margin, due to intermittent faulting-movements.

(3) The Basin is directly underlain by a body of clay over 400 feet thick. Intercalated with the clay, however, are occasional thin layers of coarser sediment.

(4) Beneath the clay are successive beds of sand and gravel aggregating several hundred feet in thickness. Thin layers of clay occur at different levels.

(5) No thick beds of salt nor even any thin salt-crusts are mentioned in any of the well-logs; and it is a notable fact that none of the companies engaged in the soda industry on the borders of the lake know of the existence of any buried saline deposits that might pay for exploitation. All of the companies limit their activities solely to the recovery of salines by evaporation from the brine of the present lake.

In spite of the scantiness of the well-data, and the inadequate description of the sediments in the logs, the following inferences are probably justified:

The thick masses of clay that immediately underlie the lake are doubtless lake-deposits and indicate a long period of lacustrine conditions that continued right up to the present time. They may readily represent a period of several thousand years. The intercalated layers of sand, on the other hand, must be fluviatile deposits and indicate brief intervals of dessication during which alluvium was carried far out into the basin. The implication would seem to be that the lake at no time during this period had any great depth, and that its waters were not falling progressively from a high over-flow stage (which would have required a minimum depth of 213 feet). It may be inferred, accordingly, that the lacustrine conditions were in general analogous to those of the present time.

The great thicknesses of sand and gravel that lie beneath the clay undoubtedly indicate a prolonged period of dessication. The fact is the more certain because the well that most definitely reveals these conditions is situated near the axis of the valley and within a few hundred feet of the lake-shore. The intercalated layers of clay, however, show that even in this dry period the Basin was occasionally flooded, temporarily and to small depth. Dessication evidently was not complete and uninterrupted for any great length of time. Such conditions, however, are to be expected in a lake-basin that annually receives the runoff from large quantities of snow on neighboring mountains. It cannot be doubted that throughout the xerothermic middle third of the Post-Pleistocene interval considerable snow fell upon the Sierra Nevada in winter, though less than at the present time, and that owing to the greater warmth of the summers the snow melted very rapidly, giving rise to short-lived floods in the streams. The lake-basin therefore probably was often covered by a sheet of water in early summer, only to be again dessicated by rapid evaporation later in the year.

The absence of any mention in the well-logs of buried beds or crusts of salt may possibly be explained by the insufficient depth of the borings. The deepest of these in the vicinity of the lake go down only 750 feet beneath its floor, and the salt of the ancient Pleistocene lake may conceivably lie at still greater depths. However, it seems more likely that the explanation is to be found in the paucity of the salt that was left when the ancient lake dried up. That lake, it is clear from Gale's studies [13], was kept essentially fresh by overflow for long periods, and the bulk of the dissolved salts carried by Owens River was deposited in the Searles

Lake Basin, farther to the south. Fresh-water shells present in the higher shore-deposits of the Pleistocene Owens Lake, moreover, definitely attest the fresh condition of its waters during the higher stages. It is very probable, furthermore, that when overflow finally ceased, the lake dried up rather quickly, for the Post-Pleistocene climate warmed up rather rapidly, as is known from several independent lines of evidence. As a consequence the period of salt-accumulation was brief. The small amount of salt precipitated may have been in part blown away, in part diffused in the subsequently deposited sediments.

It will readily be seen from all this that, although dessication probably was intermittent rather than permanent during the warm middle third of the Post-Pleistocene interval, the field-facts, as far as they have been explored, appear to confirm the essential soundness of Antevs' thesis of the extinction and subsequent rebirth of Owens Lake during Post-Pleistocene time. It seems justifiable, therefore, also to maintain the thesis of the parallel extinction and subsequent rebirth of the glaciers on the Sierra Nevada. And, furthermore, inasmuch as it is reasonably certain that the modern lake did not inherit any salt from its Pleistocene predecessor, its present salt-content may properly be taken as an index of its age, and by inference also of the age of the Sierra glaciers.

It is a matter of no little interest, in this connection, that only a few years ago almost identical conclusions were drawn by Hanson [14] regarding the Post-Pleistocene extinction and subsequent rebirth of certain small glaciers in British Columbia. That fact, the writer is obliged to admit, had not come to his attention when he was preparing the Committee's report for 1939. He therefore hastens to mention it here, both in order to give Hanson the credit that is due him and in order to stress the significance of the remarkable concordance of Hanson's conclusions and his own.

Hanson, having noted the fact that the delta of Bear River, at the head of Portland Canal, the narrow fiord that separates the southern tip of Alaska from British Columbia, is composed very largely of silt derived from the glaciers at the head of Bear River Valley, and, further, that it is too small to date back to Pleistocene times, undertook to measure the rate at which the delta is growing forward from year to year. From the data thus obtained he calculated its age, which turned out to be about 3,500 years. He therefore felt justified in concluding that the glaciers at the head of the valley also are only about 3,500 years old and represent, in fact, a new generation of ice-bodies that was born with the return of relatively cool and moist conditions. The ancient ice-streams of the glacial epoch, he inferred, had melted away entirely during the warm middle portion of the Post-Pleistocene interval.

That Hanson's paper has attracted but little attention in the United States may be due to the fact that it deals with an apparently isolated case having perhaps only local significance. It may, however, be due also to the fact that American glaciologists and geologists thus far have occupied themselves but little with questions relating to the variations of glaciers and of climatic conditions during the Post-Pleistocene interval. Be that as it may, Hanson's conclusions regarding the rebirth of the small glaciers in the Bear River Valley now suddenly assume considerable importance because of their close concordance with the writer's conclusions regarding the rebirth of the glaciers of the Sierra Nevada. The concordance of the two cases, indeed, strengthens both of them and is all the more significant because the two localities involved are situated nearly 20° apart in latitude. They justify the inference that not only the cirque-glaciers on the Sierra Nevada and on other mountains in the western United States, but also those on the mountains of Canada and Alaska belong to the modern, reborn class.

It would of course be appropriate here to discuss also the observations by Forrest Kerr in the Coast Range of British Columbia and in Alaska [15], those by R. Speight in New Zealand [16], by Ronald Ives in Colorado [17], by Max Demorest in Greenland [18], by Robert Sharp in the Ruby-East Humboldt Range of Nevada [19], and by Kirk Bryan in Colorado [20], all of which have important bearing on the subject of the recent rebirth of glaciers. To do so, however, would lengthen this report far beyond its proper limits, and it therefore seems best to reserve their discussion for another paper in which it can be done adequately.

Meanwhile, it seems in order here to state, for the benefit of those who may not have followed the recent advances in European glaciology, that in Europe the occurrence of a prolonged warm period--warmer than the present--during the middle portion of the Post-Pleistocene interval is now generally accepted as a definitely established fact. It is commonly referred to in the literature as "die postglaziale Wärmezeit." The irrefutable proofs of it are found especially in the occurrence of remnants of vegetation in Post-Pleistocene moraines, showing unmistakably that for a long period following the Pleistocene ice-age the timber-line in the Alps lay 1,000 to 1,300 feet higher than it does today. It follows that the snow-line lay at a correspondingly

higher level, and, therefore, that the glaciers in the Alps were very much smaller than they now are. Kinzl [12, p. 360], after summing up the factual knowledge that was at hand in 1932 concerning Post-Pleistocene ice-advances, announced it as his conviction that: "The present extension of the glaciers constitutes in reality an independent glaciation that is separated from the last recessional stages of the [Pleistocene] ice-age by the post-glacial period of warm climate."

It is to be noted, however, that neither Kinzl nor any of the other European glaciologists had any proof that during that warm period the glaciers actually vanished completely from large mountain-areas, only to be reborn again with the subsequent return of cooler and moister conditions. Nor did they have any data indicating the time of that rebirth. The first proof of the complete extinction and subsequent rebirth of glaciers thus comes from the United States--more specifically, from the southwestern United States, where a glacier-bearing mountain-range exists in juxtaposition to extensive desert-basins, and where, consequently the Post-Pleistocene history of the glaciers can be checked by that of the snow-fed saline desert-lakes.

That the period of glacier-extinction in the western United States was essentially contemporaneous with the "post-glaziale Wärmezeit" in Europe there can hardly be any doubt, for the upward shift of the snow-line in the Alps of over a thousand feet cannot have been the result of a mere local climatic fluctuation. It indicates a climatic change of sufficient magnitude to have been of world-wide extent. It is entirely possible, indeed, though as yet there is no definite proof, that the Stadter Buried Forest on the slopes of Mount Hood, Oregon [23, 24], which consists of the relics of a mature "rain-forest" that protrude from under a Post-Pleistocene moraine at the level of the present timber-line, records the same climatic change, the same "Wärmezeit," in the northwestern United States. And it is likewise possible that that warm period is recorded also by the fossil forests, entombed by glacial outwash gravels, that have been found in the Glacier Bay District, in southwestern Alaska [25, 26].

OBSERVATIONS ON GLACIERS IN THE CONTINENTAL UNITED STATES AND ALASKA 1938 - 1939

The Committee submits the following condensed report on American glaciers during the seasonal year from the autumn of 1938 to the autumn of 1939.

Glaciers of the Cascade Mountains--The glaciers on Mount Rainier continued to recede with essentially undiminished rapidity, as is evident from the following figures reported by C. Frank Brockman, Park Naturalist of Mount Rainier National Park:

Glacier		Recession in feet 1937-38	1938-39
Nisqually		90	85
South Tahoma (point B)		76	67
Carbon		18	25
Emmons		107	57
Paradise	point A	...	75
	point B	15	45
	point C	...	64
Stevens	point A	345	210
	point C	...	31

Measurements by the Research Committee of the Mazamas Mountaineering Club on two glaciers of Mount Hood, revealed a more rapid recession for each of them than has ever been observed in previous years. According to the report of Kenneth N. Phillips, Chairman of the Committee, the Eliot Glacier receded 64 feet, as compared with 22 feet in the preceding year, and the Coe Glacier receded 59 feet, as compared with 20 feet in the preceding year.

A visit to Mount McLoughlin, in the southern Cascades of Oregon, led to the discovery that the Sholes Glacier, on the north side of that peak, has vanished entirely. An account of this discovery is given by Phillips in Mazama of December, 1939 [21]. It is illustrated with a photograph showing the Glacier as it appeared in 1898, and another photograph taken from the same spot in 1939, showing the empty cirque. The case is of peculiar interest in that the Glacier has disappeared within the lifetime of the man in whose honor it was named--C. H. Sholes, a past president of the Mazamas.

The Sholes is the third glacieret in the southern Cascade Mountains whose complete extinction has been noted in recent years. A number of other glacierets on the higher volcanoes of the range appear to be on the verge of extinction [22]. A close watch will be kept on them by the Mazamas.

A beginning was made by the Mazamas in 1939 in recording the recession of the glaciers on Mount St. Helens, in Washington State. A photograph was taken by Donald B. Lawrence, who was engaged in timber-line studies on the peak, to show the position of the terminus of the Muddy Glacier.

Glaciers of the Sierra Nevada--According to the report of Assistant Park Naturalist M. E. Beatty, the principal glaciers in Yosemite National Park and just outside its borders were again measured in September, 1939. As no measurements could be made in 1938, owing to large quantities of snow masking the termini of the glaciers, the figures reported this time show the changes that have taken place in a two-year period. In 1939 as in previous years difficulty was experienced in determining the exact position of the termini, as the ice really continues beneath the terminal moraines. Moreover, cave-ins due to the undermining action of melt-water further complicated the situation. It seemed desirable, nevertheless, to continue to make these measurements of recession, as they do throw some light on the volumetric changes that are taking place in the glaciers. They should be considered in conjunction with the measurements that show the reduction in thickness of the glaciers due to surface-ablation.

Glacier	Recession in feet 1936-37	1937-39	Notes
East Lyell	- 6	-36	
West Lyell	-14	+ 2	Advance due probably to caving-in of moraine
Maclure	-13	+ 1	Advance due probably to caving-in of moraine
Dana, station 3A	-10	-28	
Dana, station 5A	-33	-60	
Conness	-90	-42	

To determine the reduction in thickness of the glaciers, measurements were made with an Abney level to stakes set in lines across their surface. The West Lyell at stake 2 was found to have suffered a reduction of 20.1 feet in six years, the mean annual loss being 3.4 feet.

For the East Lyell a more complete record of progressive reduction is available:

Period	Measured reduction	Mean annual reduction
1933-35	9.5 feet	3.97 feet
1935-36	2.4 feet	
1936-39	20.1 feet	6.7 feet
Total in 6 years	32.0 feet	5.3 feet

From these figures it is evident that the East Lyell Glacier lost nearly twice as much in volume during the three-year period 1936-39 as during the three-year period 1933-36. The greatest loss occurred probably during the seasonal year 1938-39, as a result of unusually light snowfall followed by a summer marked by many cloudless days.

The observations on the great terminal moraine of the Conness Glacier, which showed it to be in reality a mass of "dead ice" preserved by a thin mantle of rock-débris, have already been noted on an earlier page. The fact that the great wall consists of the former front of the Glacier impressively indicates the relatively large dimensions which the Glacier attained during its last advance, presumably about the middle of the nineteenth century. The Conness Glacier, as it appears at the present time, contains but a small fraction of the volume which it possessed at that time.

Oliver Kehrlein, Chairman of the Committee on Glacier-Studies of the Sierra Club, reports that during the past year a systematic inventory or census, was made of all the cirque-glaciers and glacierets now existing in the headwaters-basin of the San Joaquin River. Location, size, altitude, orientation, character of moraines, and other characteristics are noted, and these data are supported by numerous photographs. During the summer of 1940 this glacier-census will be extended farther southward in the Sierra Nevada, and ultimately it will be extended over the entire range. Thus a catalogued record will be obtained of the present condition of all the ice-bodies on the range that will be invaluable for comparative studies in future years. A supple-

mentary collection of descriptions and photographs of glaciers that date from former years is also being brought together.

Inasmuch as the present glaciers of the Sierra Nevada hold the key to the Post-Pleistocene history of all the glaciers in the western United States, this effort by the Committee of the Sierra Club is particularly worthwhile, and the Committee is to be commended for the energetic manner in which it has begun this big task. It is to be hoped, furthermore, that other mountaineering organizations will emulate its example and set about to catalogue systematically data on the glaciers with which they are most familar. Thus, through the enterprise of many different groups there will be obtained in the course of time a complete census of all the existing glaciers in the continental United States.

If to some such an undertaking should seem hardly worth the effort required, because of the small size of the majority of our western glaciers, it is to be pointed out that it is the very smallness of the glaciers that makes a census of them desirable. Several glacierets already have vanished during the last few decades, and many others surely will follow in the near future if the present climatic conditions continue unchanged. On the other hand, should there be a change towards slightly cooler and/or wetter conditions, our small western glaciers would be the first to register that change. They would respond more immediately and more noticeably than either streams, lakes, ground-water, or vegetation.

Glaciers of the Rocky Mountains--No systematic observations were made in 1939 on the recession of the glaciers in Glacier National Park, Montana, but the plan of making annually a large-scale contour-map of one of the major glaciers was continued. In 1937 the Grinnell Glacier was thus mapped by Ranger-Naturalist James L. Dyson; in 1938 the Sperry Glacier was mapped by him, and in 1939 the Jackson Glacier (which in previous reports of this Committee has been referred to as the Siksikaikwan Glacier or the West Lobe of Blackfoot Glacier). These topographic maps are made by the plane-table and stadia-method on the scale of 1:2400 and with a contour-interval of 20 feet. They are to serve as accurate bases for comparison with future resurveys to be made at intervals of five years.

A more detailed account of the mapping of the Jackson Glacier will be found in an artible by James L. Dyson published in this volume of the Transactions.

Glaciers of Alaska--From the report of Frank T. Been, the newly appointed Superintendent of Mount McKinley National Park, it is evident that the work of securing data on the recession of the glaciers in the Park, which was begun by his predecessor, is being actively carried on under the direction of Mr. Been.

Measurements were made to the fronts of the Toklat, Sunset, and East Fork glaciers, and photographs of the two last-named were transmitted with the report. The principal difficulty which the measuring parties encountered was the lack of rock-outcrops, or other stable objects in the vicinity of the glacier-termini that might serve as permanent reference-points, the valley-floors in front of the glaciers being covered with shifting outwash material for many miles. In the case of the Toklat Glacier it was found necessary to go 688 feet from the terminus in order to find a suitable reference-point. The reference-point for the East Fork Glacier was established at a distance of 969 feet from the terminus. It is hoped, nevertheless, that in spite of this inherent difficulty due to the nature of the terrain it will be found possible to obtain quantitative data on the rate of recession of these glaciers.

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COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1939-40

Joseph Kittredge, Chairman

The personnel of the Committee includes the following: T. C. Adams, N. W. Cummings, W. E. Davis, S. T. Harding, A. H. Hendrickson, I. E. Houk, J. Kittredge (Chairman), E. W. Lane, C. H. Lee, C. G. Rossby, T. Saville, C. A. Taylor, C. W. Thornthwaite, H. C. Troxell, and H. G. Wilm.

During the year a reorganization has been effected to bring together for the consideration of a single Committee the closely related subjects of evaporation and transpiration, which were formerly separated between two Committees. While evaporation from free water-surfaces is a specific phase of hydrology, the losses of water by evaporative processes from vegetation and soil have similar features and may be subject, in part at least, to the physical principles which have been fruitful in the study of evaporation from water-surfaces. The latter is the simpler case and progress is more advanced, although marked differences of opinion still exist as to the best methods of relating evaporation to meteorological factors. One of the aims of this Committee should be to show how these differences may be obviated or reconciled. Vegetation and soil introduce certain physical complexities, and transpiration involves in addition the physiological responses of the vegetation. Moreover, in the case of transpiration there is great need for

coordination between the work being done from the hydrological point of view and that on the biological aspects, which have been summarized by Raber [see 8 of "References" at end of report].

Recent new developments in methods or projects comprise several interesting items. A method of determining the evaporation from and condensation on moist surfaces, based upon the gradient of moisture-concentration in the layer of turbulent air above the surface has been developed by Thornthwaite and Holzman [11]. Preliminary results are promising and the authors find that the necessary measurements of wind-velocities and vapor-pressures at two levels are feasible. The chief difficulty is in obtaining sufficiently accurate measurements of atmospheric humidity, and study is being devoted to the improvement of instruments for this purpose.

The application of the principle of the conservation of energy to transpiration-losses of moisture from plants has been carried forward by Cummings, whose preliminary results indicate this to be a promising new approach to the evaluation of transpiration.

A new project on evaporation from snow is being initiated by the Rocky Mountain Forest and Range Experiment Station on the headwaters of the Colorado River near Fraser, Colorado. Measurements of evaporation are being made from pans and containers of different sizes and designs, with suitable replications, so that the usefulness of the smallest and most convenient portable unit can be evaluated by comparison with units of much larger area and with surfaces simulating natural conditions.

Evaporation from unfrozen water-surfaces when the temperature of the air is less than 32° F has been the subject of a recent symposium led by Pettis and Hickman [7], in specific application to the Great Lakes.

Recent installations of shallow ground-water wells by the Soil Conservation Service in Ohio and Texas, and by the Appalachian Forest Experiment Station in North Carolina, will add much to the knowledge of the diurnal fluctuations of the water-table in response to transpiration and evaporation, and will doubtless lead to further study of the possibility of deriving from these records values of depths of water-losses.

A comprehensive and suggestive study of transpiration in Java, reported by Coster in 1937 [2], has received little or no attention in this country, although it has considerable interest. Average annual transpiration use of water in inches depth over the areas of 11 different types of grass, shrubby, and forest vegetation were determined as the product of the rate of transpiration in grams per hour per gram of green weight of foliage separately during hours of Sun, and hours without Sun in the period from 8:00 a.m. to 4:00 p.m., multiplied respectively by the average percentages of Sun and cloudiness, multiplied by the green weight of foliage per hectare, multiplied by eight hours per day and 365 days per year. The rates of transpiration were determined by repeated weighings of cut leaves, of cut plants, and of potted plants, checking one against the other. In a tropical region with annual precipitation of 140 to 170 inches, the annual transpiration-losses in different vegetative types varied from 16 to 122 inches.

In the matter of coordination, except for the evaporation from water-surfaces, the integration of the study of transpiration and evaporation is almost automatic, because the two processes take place concurrently from the same areas and soils. In fact their separation on the same area is a difficult matter, but fortunately for most purposes in hydrology it is unnecessary. In the interest of usable results for hydrological purposes, it may be appropriate at this point to emphasize the importance of consideration by workers on transpiration in other fields of determining water-losses from vegetation and soil in terms of or convertible to inches depth.

Several suggestions may be made as to aspects or problems in need of further study. One is the need for more and better information on transpiration-losses from areas of natural vegetation. Wild lands occupy large areas and are important sources of water-supply but by comparison with the data as to water-losses from cultivated areas, the information in regard to uncultivated areas is extremely meager and unsatisfactory.

For the benefit of those who wish to derive evaporation-losses from water-surfaces by the use of the vapor-pressure difference, current measurements of water-temperatures and humidities at Weather Bureau Class-A Stations would be the greatest help and may be strongly urged. Similarly from the point of view of the evaluation of evaporation through the principle of the conservation of energy, and consequently of the usefulness of the records from Weather Bureau pans for this purpose, an adequate study of the heat-leakage through the walls of these pans is essential.

Several of the estimates of transpiration-losses from natural areas have been derived from determinations of losses from plants growing in pots, tanks, or lysimeters. In view of the con-

siderable development of tank- and lysimeter-studies during recent years some preliminary consideration has been given by the Committee to the possible discrepancy between transpiration-losses under these conditions and from the same soil and plants growing outside of containers. With exceptions noted subsequently, the consensus of opinion within the Committee may be briefly summarized. The rates of transpiration inside and outside of containers are not the same. Plants in containers transpire more than those under similar natural conditions. The difference is not negligible or unimportant. It is doubtful whether it can be made negligible. Insulating or burying the containers, surrounding them with similar vegetation, and increasing the size should tend to reduce the discrepancy. The use of natural cores or blocks of soil, or increasing the depth beyond that of root-penetration, or providing drainage, probably will not reduce the discrepancy appreciably. It is doubtful whether a correction-factor can be derived to make results from containers applicable to natural areas. The reliability of values of transpiration per unit of foliage or of growth for application to larger areas is also doubtful. Relative values between different species may or may not be reliable. The continuation of existing experimentation with plants in containers is justified, but expansion is inadvisable until a more adequate evaluation of results has been made. In this connection there is great need for data and analysis of results from the large lysimeters which have recently been installed by the Forest Service and Soil Conservation Service.

Actual soil or rock-substrata should make the best base for lysimeters. The distribution of moisture and root-development in containers is not normal. Any physiological disturbance of the normal life-processes of plants increases their water-requirement [10]. The heterogeneity of soils over any drainage-area requires a large and perhaps prohibitive number of replications to provide adequate sampling to justify applying the results to the area as a whole. Useful results may be obtained by the evaluation of all factors in the energy-balance. The results from containers can never be applicable to natural surfaces, because differences in transpiration are caused by differences in the coefficients of turbulent transfer which can not be measured properly for a plant in a container. "It is impossible to estimate from potometer-experiments the exact amount of water used per acre by a given crop under field-conditions. The amount of available soil-fertility, soil-moisture, and other conditions never are and probably cannot be made to be strictly comparable to field-conditions. This fact does not, however, prevent the establishment of general principles.... concerning the relative water-requirement of different crops" [4]. Factors of 29 to 55 per cent have been estimated for adjustments of consumptive use by tules in isolated exposed tanks to large areas in Southern California. For grasses, the difference between tanks and natural conditions was assumed to be negligible [1]. Shantz reached the general conclusion that plants in the field had a transpiration-ratio ten per cent greater than those in shelter (screened enclosures), and plants in freely exposed tanks 13 per cent greater than those in shelter [9].

Mr. Lee, who has had wide experience with tanks, feels that the foregoing paragraphs give an inaccurate and unnecessarily pessimistic evaluation of the method. His comments should have weight and are quoted as follows:

"The difference, although not negligible or unimportant in much of the past experimental work, can be made inappreciable from the practical standpoint by proper tank-design and exposure and by careful and systematic observation. This conclusion is supported by instances where results of tank-measurements have been checked by other independent methods [3, 5, 6].

"For tanks, the following rules should be followed in design and exposure:

"(1) Provide sufficient soil to attain normal transpiration-relationships and root development of the plant.

"(2) Obtain the same physical conditions of the soil after excavation and replacement in the container, especially with respect to aeration and permeability.

"(3) Obtain the same atmospheric exposure and light-exposure as for natural field-conditions.

"(4) Obtain the same leaf-development or density of planting as occur under field-conditions.

"(5) For plants naturally growing in freely drained soil, the amount of water added to the tank at each application should be limited, in order to prevent percolation to the bottom of the tank with building up of capillary-storage or a water-table.

"(6) For plants drawing their supply from the capillary-fringe, the water-table must be maintained at constant level.

"For lysimeter-design and exposure, the first five of the above rules should also be applied and in addition the following:

"(1) Uniform distribution of downward percolating water throughout the soil-column should be secured.

"(2) Soil-columns should be of sufficient length for the zone of capillary-storage to be below the reach of plant-roots. It is to be recognized that capillary-storage may occur at the bottom of an interrupted soil-column without the existence of a water-table.

"The field-plot method, where applicable, gives more dependable results than either the tank- or lysimeter-method. The accuracy of the field-plot method depends largely upon the possibility of eliminating deep percolation" [1, 3].

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ADVISORY COMMITTEE OF SOIL CONSERVATION SERVICE, 1939-40

R. E. Horton, Chairman

The membership of this Committee is as follows: J. E. Church; W. W. Horner; A. F. Meyer; Caleb M. Saville; L. K. Sherman; Samuel Shulits; Roy N. Towl; F. J. Veihmeyer; Robert E. Horton (Chairman).

To facilitate the work of the Committee an Executive Sub-Committee was formed, consisting of W. W. Horner, L. K. Sherman, and Robert E. Horton as Chairman.

The principal activities of the Committee are through the Executive Sub-Committee, which holds meetings each month or oftener at Washington. Matters in which the other members of the Committee are interested or can be helpful are reported to them from time to time.

The Advisory Committee has at various times urged the publication of data and results of runoff, soil-erosion, and infiltration-capacity experiments carried out at the various field-experiment stations of the Soil Conservation Service. This activity of the Committee has borne fruit, as steps have been taken, and are nearly completed, which will authorize the publication of a series of hydrologic bulletins by the Department of Agriculture. These bulletins will be available for the presentation of research-data, analyses, and results, and it is hoped to present data of field-experiments in sufficient detail so that they may be analyzed and used by anyone and in any manner to which they are adapted, not only in connection with the work of the Soil Conservation Service and other governmental agencies but by practicing engineers in municipal, irrigation, water-supply, water-power, sewerage, drainage, and other lines of hydraulic and hydrologic work. Cooperation of the engineering profession, including various members of the Association of Hydrology, in securing the establishment of this series of bulletins is hereby acknowledged.

Another activity of the Committee which has borne fruit is in connection with runoff and infiltration under winter conditions, especially with frozen ground and with snow-cover.

After various conferences between the Executive Sub-Committee and Dr. M. L. Nichols, Chief of Research, and members of his staff, arrangements were made to keep more complete records, particularly of frost-penetration and duration in the soil on field-plats and small watersheds, together with data of snow-cover, temperature, and other records, which are already taken. A few of the results of these studies previously carried out at certain stations were presented at the California meeting of the Association of Hydrology last winter.

Starting with a memorandum prepared by the Executive Sub-Committee recommending more comprehensive research in relation to snow-cover, snow-melting, soil-frost, and infiltration through frozen soil, Dr. Nichols designated W. U. Garstka of the Division of Hydrology, under C. E. Ramser, to take charge of research-work in cryologic hydrology. Arrangements have been made to establish and maintain a field-experiment station for this purpose, in cooperation with the Michigan Agricultural Experiment Station at East Lansing, Michigan.

The Advisory Committee has spent much time working with representatives of the Research Division of the Soil Conservation Service on matters of methodology of collecting and analyzing data from sprinkled runoff-plats and small drainage-areas. Sprinkled-plat experiments have proven particularly valuable in relation to the scientific aspects of hydrology, since they permit all of the variables to be controlled with the exception of slopes, which must of course be used as nature has provided them in conjunction with different types of soil- and cover-conditions. Some of the results of one of these series of sprinkled-plat experiments, at Tucson, Arizona, will be presented at this meeting in a paper by Beutner, Gaebe, and Horton.

The Chairman of the Committee actively participated with G. W. Musgrave, in charge of infiltration-studies, in carrying out another extensive series of sprinkled-plat experiments in Texas, analyzing the results and comparing them with the results of areal determinations of infiltration-capacity derived from measured rainfall and runoff.

W. W. Horner has prepared a manual covering the simpler features of the analysis of field-experiments on small watersheds, which it is expected will shortly be published by the Soil Conservation Service. Mr. Horner has also kept closely in touch with and carried out analyses of results of field runoff-experiments on small watersheds at Experiment Station of the Soil Conservation Service at Edwardsville, Illinois.

At the request of Dr. Nichols the members of the Executive Sub-Committee, particularly the Chairman, are engaged in preparing other manuals to extend methodologies in connection with field-research in hydrology.

The above statement covers only a part of the many activities of the Research Advisory Committee. In addition various members of the Committee have inspected various field-stations and both personally and by correspondence have worked with the Project Supervisors in relation to many matters connected with field-research in hydrology.

Throughout the year there has existed the most cordial and helpful relations with the Committee on the part of Dr. M. L. Nichols, Chief of the Division of Research, and the members of his staff. There has also been close cooperation between the Executive Sub-Committee and the members of the Flood Control Division of the Department of Agriculture.

Voorheesville, New York

COORDINATING COMMITTEE ON HYDROLOGY BETWEEN THE AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS AND THE AMERICAN GEOPHYSICAL UNION, 1939-40

H. S. Riesbol, Chairman

The Committee is as follows: B. S. Barnes; D. B. Krimgold; D. S. Jenkins; J. G. Sutton; J. C. Marr; H. S. Riesbol (Chairman).

The Committee has, during the current year, endeavored to project its activities along the lines of the report presented at the twentieth annual meeting of the American Geophysical Union.

(1) The Committee has established active participation between the American Society of Agricultural Engineers and the American Geophysical Union in the preparation of the annual bibli-

ography on hydrologic publications. D. B. Krimgold and H. S. Riesbol are representing this Committee and the American Society of Agricultural Engineers on the Committee on Bibliography of the Association of Hydrology, with the objective of insuring adequate coverage of agricultural engineering publications. Abstracts of articles of hydrologic nature which appeared in the journal Agricultural Engineering during the year 1939 have been submitted to the Committee on Bibliography.

(2) Attention of the Special Committee on Flood Waves and of the Committee on Runoff of the Section of Hydrology has been called to a paper entitled "The measurement of velocity of overland flow" presented by Dr. R. E. Yoder at the December (1939) meeting of the American Society of Agricultural Engineers in Chicago, Illinois. Dr. Yoder is stationed at the Ohio Agricultural Experiment Station, Wooster, Ohio.

(3) Attention of all members of the Section of Hydrology is called to the index "Instruments commercially available for use in the study of hydrology and meteorology" which was prepared by W. H. Pomerene as a contribution of the Committee on Hydrology of the American Society of Agricultural Engineers. The index may be obtained at a nominal charge of 20¢ from the Secretary of the Society at St. Joseph, Michigan.

(4) It is the desire of this Committee to bring to the attention of members of the Section of Hydrology practical and engineering applications which are made of hydrologic science. The Committee therefore presents the following list of papers which appeared in the journal Agricultural Engineering during the calendar year 1939:

W. C. Lowdermilk, Flood control in soil conservation, v. 20, No. 1, pp. 17-20, 1939.
O. W. Israelsen, Water application efficiencies, v. 20, No. 2, pp. 55-56, 1939.
J. C. Stephens, Theory of terrace gradient, v. 20, No. 4, pp. 149-152, 1939.
John G. Sutton, Hydraulics of open ditches, v. 20, No. 5, pp. 175-178, 1939.
E. G. Diseker, A method of measuring run-off velocity as releted to soil movement between terraces, v. 20, No. 5, pp. 194-196, 1939.
F. E. Hardisty and H. B. Ingersoll, An approach to the study of flood peak formation, v. 20, No. 6, pp. 225-227, 1939.
R. W. Baird, Watershed and hydrologic studies on the Blacklands Experimental Watershed, v. 20, No. 7, pp. 273-276, 1939.
Kyle Engler and D. G. Carter, Ground water resources, v. 20, No. 7, pp. 283-284, 1939.
F. E. Staebner, Supplementary irrigation on the Atlantic Coast, v. 20, No. 7, pp. 271-272, 1939.
F. E. Staebner, A soil moisture meter, v. 20, No. 8, pp. 317-319, 1939.
H. L. Cook and F. B. Campbell, Characteristics of some meadow strip vegetations, v. 20, No. 9, pp. 345-348, 1939.
R. A. Work, Soil moisture control by irrigation, v. 20, No. 9, pp. 359-363, 1939.
H. F. McColly, Snow ridging for moisture conservation, v. 20, No. 10, pp. 383-384, 1939.
O. W. Israelsen, Water application efficiencies in irrigation and soil conservation, v. 20, No. 11, pp. 423-425, 1939.

(5) It is the recommendation of this Committee that a joint survey be made of needs for hydrologic research and of research-projects now under way in the field of Agricultural Hydrology. This project would be cooperative between the Committee on Hydrology of the American Society of Agricultural Engineers and a designated committee of the Association of Hydrology of the American Geophysical Union. R. B. Hickok, Associate Hydraulic Engineer, Soil Conservation Service, Purdue University, Lafayette, Indiana, is now leading preliminary work on such a project for the Committee on Hydrology of the American Society of Agricultural Engineers. The results of such a survey should serve to supplement previous reports of similar nature as prepared by special Committees of the American Geophysical Union and should tie in closely with the reports on "Deficiencies in hydrologic data" and "Deficiencies in hydrologic research" prepared by the Water Resources Committee of the National Resources Planning Board. It is also recommended that results of the survey be published in mimeographed form for transmittal at a nominal fee to all interested parties.

U. S. Soil Conservation Service,
Coshocton, Ohio

COMMITTEE ON INFILTRATION, 1939-40

G. W. Musgrave, Chairman

The membership of the Committee, including as it does representatives from most of the institutions, agencies, or organizations concerned with infiltration-problems, has been in a position to maintain contact with practically all of the current infiltration-work of the country.

The United States Geological Survey, in connection with the continued measurements of stream-flow, has given attention to hydrograph analysis and associated rainfall. This is serving to develop our information on the infiltration of many large and important watersheds of the country.

The United States Forest Service has continued its studies of the effect of land-usage upon hydrological phenomena and included infiltration on numerous plots and watersheds.

Attention has been given during the year by the Soil Conservation Service to the analysis of numerous records dealing with hydrologic phenomena in both the field and laboratory.

Various members of the Committee have themselves been directly concerned with the development of certain phases of the proolem.

During the past two years, L. K. Sherman has been supervising a project on infiltration in Illinois which was sponsored by the Illinois State Planning Commission. One of the objectives was to develop a methodology for determining infiltration-capacities over large basins of from 500 to 1500 square miles. A procedure has been devised and set forth in a report by the Illinois State Planning Commission suitable for practical applications by engineers and agriculturalists. One of the papers on this program presents a phase of this work.

W. W. Horner has given particular attention to methods of analyzing hydrographs from small watersheds, particularly the one at Edwardsville, Illinois. His paper on this program is an outgrowth of this work.

Messrs. Hathaway, Hertzler, and Langbein of the Committee have served on an Inter-Departmental Committee whose attention has also been directed toward hydrograph-analysis and the development of infiltration-values from existing records of watersheds of divergent characteristics.

G. A. Hathaway has pointed out that practically all of the 47 district offices of the War Department are studying rainfall and runoff, particularly with the objective of obtaining infiltration-loss values or indices. These values are for drainage-areas of ten square miles or greater, and not for plots.

M. R. Lewis has reported that in cooperation with the Oregon State College and others, work is planned for arriving at some explanation of the rainfall-runoff relations on the Newberg Project. It is believed that the first point of attack should be on the location of impermeable strata governing infiltration, and it is proposed, therefore, during the coming summer to make installations preparatory to undertaking this work.

The United States Geological Survey has resumed studies of infiltration north of Houston, Texas, on the out-crop areas of sands which yield water to the wells of Houston and adjacent territory. This work is under the immediate direction of Walter N. White.

Arend, et al., in connection with the survey of the St. Francis watershed in Missouri, made comparisons of two methods of determining relative infiltration. Essentially similar relative values were secured on large and small plots, although the latter consistently showed slightly higher values. Comparisons of the effect of rain-intensities also were made. No significant differences were obtained in minimum infiltration-capacities when three- and six-inch-per-hour intensities were used, except when the higher intensity preceded the lower. This difference was more pronounced on bare soil and less noticeable with good grass-cover.

A. R. Croft advises that in the arid Inter-Mountain Region, recharge of mountain-watersheds which supply the semi-desert valleys with water, occurs to a very large extent by infiltration from melted snow-water during the short melting-period in the spring. The manner of disposition of this water through (1) surface-runoff, (2) subsurface-runoff, or (3) deep infiltration, is believed to have important relationships to accelerated soil-losses, forage-production, and seasonal disposition of stream-flow--particularly base-flow.

Infiltration-studies at the Rocky Mountain Forest Experiment Station have been planned for immediate undertaking under the direction of H. G. Wilm. Measurements will be made upon replicated sample areas, within one or more watersheds from which runoff-rates are also being determined, as a means of ascertaining the applicability of hydrographs from small areas to large ones. Additional objectives include comparisons of two or more methods of measuring infiltration under a plan which will run parallel with experiments planned by your Chairman.

At the California Forest and Range Experiment Station studies are under way dealing with the application of infiltration-data to the analysis of hydrographs of small watersheds and the effect of soil, vegetation, slope, soil-moisture, water-temperature, and rainfall-intensity and duration, upon infiltration-capacities. Research Note No. 14, from this Experiment Station has reported differences in infiltration-capacities of a forested soil in contrast to one denuded by smelter-fumes. Comparisons have also been made between areas which are annually burned and areas of undisturbed brush, as well as areas which are grass-covered. A number of additional infiltration-studies have been planned.

Thus on watersheds at Edwardsville, Illinois, and at Fort Collins, Colorado, the Soil Conservation Service, under the direction of your Chairman, is inaugurating studies of infiltration dealing with the principal factors which affect it, seasonal variations, comparisons of methods, and related items. Certain phases of this work are fully coordinated with the work of Mr. Wilm, as outlined above.

Your Chairman had under his direction during the current year several direct studies of infiltration. One of these located in the Concho River Basin in Western Texas had to do with a direct comparison of four different methods of measuring infiltration, together with the control of certain of the more important factors affecting infiltration. Comparing concentric rings, tubes, and rainfall-simulators of two different sizes, each method being amply replicated on each of 48 different sites, proved that each of the types of equipment give essentially similar relative values, and were able to segregate soil and vegetal-cover differences, although the absolute values varied primarily in accordance with the degree of turbidity resulting on the land-surface from one or another of the methods. Some preliminary information as to the effect of temperature and rain-intensity upon infiltration developed, and further evidence was secured on the very large effect of soil-structure upon infiltration. Soils whose particles are aggregated to a considerable extent, and which, consequently, have large pores, were found to have high infiltration-rates. A high degree of aggregation was commonly associated with good land-use practices such as well-managed grazing-lands in contrast to overgrazed lands or intensively cultivated lands.

Borst and Musgrave, in continuing a study of seasonal variation in infiltration, established at Zanesville, Ohio, in 1938, find large variations on the same soil occurring at different times of the year. These changes appear to be primarily associated with differences in temperature of water and of soil, and also differences in soil-moisture content. Commonly high temperatures were associated with low soil-moisture content and, conversely, low temperatures in general were associated with high soil-moisture content, so that the two factors of temperature and moisture could not be segregated under the methods which were employed. On ground frozen to a depth of not more than four inches and using water at a temperature of 33°, a small amount of infiltration was frequently found. However, on soils frozen to a depth of ten inches infiltration ceased. These studies are being continued with some modification to give greater control particularly of soil-moisture.

A bibliography of infiltration by J. M. Davidson of the Soil Conservation Service, comprising approximately 200 references with abstracts, has been reviewed by the members of the Committee and certain additions suggested. The bibliography is planned for early publication and is expected to be available in a sufficient quantity to meet the needs of all who are interested. It should be possible by means of annual supplements provided by your Committee to maintain a nearly complete current record of papers dealing with infiltration.

Our view of the phenomena surrounding and affecting, or determining infiltration, though now more or less outlined, has not been brought into sharp focus. There are many physical factors whose effects are suspected, but on which quantitative evidence is very meager indeed. This vagueness in many parts of the problem causes to arise many differences of opinion. The accumulation of more evidence should remove many such items from the realm of opinion to the more satisfactory one of fact.

Among the many questions now in urgent need of more evidence and scientific proof may be cited a few of the more important:

(1) To what extent or within what limits of accuracy may runoff be predicted when infiltra-

tion is known?

(2) How may we best determine infiltration-values and to what extent may they be predicted for large watersheds from measurements which are made on small sample areas within such larger ones?

(3) What are the more important factors determining infiltration, what are their quantitative relationships, and within what limits do they fluctuate?

Systematic investigation of the problem is not only certain to develop information of immediate need and value, but should throw much additional light on other related questions, such, for example, as the effect of methods of land use on infiltration-rates and capacities, and the practical possibilities of increasing infiltration through modified land-usage.

Cooperative effort by various agencies in attacking one or more of the phases of the problem is doing much to hasten their solution as well as to strengthen conclusions which are reached. Just during the past week two entirely parallel and coordinated experiments have been planned by two separate agencies, both interested in an identical problem and each having suitable facilities for its study. Your Committee should be in a position to stimulate such cooperative effort.

U. S. Soil Conservation Service,
Washington, D. C.

COMMITTEE ON PHYSICS OF SOIL-MOISTURE, 1939-40

(Soil-Porosity in Relation to Gaseous- and Water-Movement)

N. E. Edlefsen, Chairman

The following members constitute the Committee: Dr. F. J. Alway, University of Minnesota, University Farm, St. Paul, Minnesota; Dr. L. D. Baver, Ohio State University, Columbus, Ohio; Dr. G. B. Bodman, University of California, Berkeley, California; Dr. Richard Bradfield, Cornell University, Ithaca, New York; Mr. S. J. Buchanan, U. S. Waterways Experiment Station, Vicksburg, Mississippi; Dr. T. F. Buehrer, University of Arizona, Tucson, Arizona; Dr. I. A. Denison, National Bureau of Standards, U. S. Department of Commerce, Washington, D. C.; Dr. Willard Gardner, Utah Experiment Station, Logan, Utah; Dr. Glennon Gilboy, Massachusetts Institute of Technology, Cambridge, Massachusetts; Dr. O. W. Israelsen, Utah State Agricultural College, Logan, Utah; Dr. L. B. Olmstead, Bureau of Plant Industry, U. S. Department of Agriculture, Washington, D. C.; Dr. F. J. Veihmeyer, University of California, Davis, California; Mr. E. A. Willis, Bureau of Public Roads, U. S. Department of Agriculture, Washington, D. C.; Dr. N. E. Edlefsen (Chairman), University of California, Davis, California.

The annual report of the Committee is intended to be a symposium on a particular aspect of the physics of soil-moisture. L. D. Baver was invited to prepare a paper that could form the nucleus of the report. It was felt that this would stimulate discussion. His paper was sent to each member of the Committee and to a selected list of investigators with a request for their comments, opinions, and criticisms together with references to pertinent data. Dr. Baver's paper as well as most of the discussion following the paper is published verbatim without being edited in any way by the Chairman. In a few of the replies, the discussion was part of a letter, and in these cases, the Chairman has taken the liberty of telling what the investigator said.

SOIL-POROSITY IN RELATION TO GASEOUS- AND WATER-MOVEMENT

L. D. Baver

The soil is a porous medium which is made up of various sizes of pores. The amount and character of the pore-space determine the air- and water-relationships within the soil. Water that enters the soil either is retained in the pores or percolates through them to lower depths. Those pores in which water is not retained are filled with the soil-air. The relative proportions of air and water in the soil as well as the permeability of the soil-column to water and air are dependent upon the distribution of different-sized pores.

Water-movement and soil-porosity

The movement of water through the soil pore-space is brought about either by the action of gravity or of capillary forces alone or in combination. According to the dominance of the moving force, the type of water-movement may be discussed from two points of view, namely, (1) that which moves in the larger pores primarily through the action of gravity, or movement in a satu-

rated soil, and (2) that which moves primarily through capillary forces from surface to surface or in the small pores in the presence of numerous air-water interfaces, or movement in an unsaturated soil.

Movement in unsaturated soils--An unsaturated soil is one in which the larger pores are filled with air and, consequently, where movement is closely dependent upon a large number of air-water interfaces. The dominant moving force in the movement of water in unsaturated soils is the capillary potential. According to modern concepts the rate of capillary flow of water through soils is given by the equation

$$Q = -K \text{ Grad } \psi \qquad (1)$$

where Q is the mass of water which passes in one second through one square centimeter of an imaginary plane perpendicular to the direction of flow, K is the capillary conductivity, and Grad ψ is the capillary potential-gradient (the gravitational potential is also a factor in vertical capillary-flow).

The capillary conductivity, K, depends upon the kind of soil, its state of packing, and the moisture-content. Buckingham [see 1 of "References" at end of paper] showed that the capillary conductivity decreased with the size of the soil-pores. This fact is confirmed by the usual observations that the rate of rise of capillary water is much faster in a sandy soil than in clays. The texture and structure of the soil affect capillary conductivity as they influence the number, size, and continuity of the pores. Moore [2] measured the capillary conductivity of soils with different textures at different tensions and found that the capillary permeability of sands became zero at pF of 1.9 while that of clays became zero at a pF of 2.15. These data suggest that the water-films in sands become discontinuous at lower tensions than in clays due to the fact that clays possess a large number of small pores in contrast with a smaller number of larger pores in sands.

Gardner [3] observed that an optimum porosity for capillary movement seems to exist within a given soil. For example, he found that loosely--as well as closely--packed samples of a Greenville soil had lower capillary conductivities than the normally-packed soils. In the loosely-packed samples, the pores are apparently too large to permit the establishment of a continuous moisture-film. In the closely-packed soils, the pores were so small that there was considerable resistance to flow.

Therefore, it is seen that the size of the pores is important in determining the capillary conductivity of soils.

Movement in saturated soils--In saturated soils, water-movement takes place through a soil pore-space that contains little, if any, air. In most instances, however, there is probably some entrapped air.

According to Darcy's law, the velocity of flow of water through a soil-column is directly proportional to the difference in pressure-head and inversely proportional to the length of the column, or

$$V = k(h/\ell) \qquad (2)$$

where V is the velocity in cubic centimeters per second, h is the difference in head in centimeters, ℓ is the length of the column in centimeters, and k is the proportionality constant.

Slichter [4], in studying the movement of ground-water in soils, modified the Darcy equation by introducing a variable soil-characteristic into the basic formula. The permeability or transmission-constant was visualized as being dependent upon the size of the particles and the amount and nature of the pore-space. He emphasized the fact that all formulas for flow that did not take porosity into consideration were inadequate.

Zunker [5] has suggested that the Slichter transmission-constant varies directly with the square of the tension-free pore-space and inversely with the square of the soil-volume times the square of the effective specific surface. He calculates the tension-free pore-space from the total porosity, the density and the hygroscopicity of the soil. Kozeny [5] has proposed that the transmission-constant varies directly with the cube of the total porosity and inversely with the square of the soil-volume. Although these suggested modifications have not been amply proven as satisfactory, nevertheless they represent a distinct attempt to evaluate the significance of the amount and nature of the soil pore-space as a modifying factor in the original Darcy equation.

The exact relationship between porosity and soil-permeability is, therefore, as yet in the experimental stages. There is sufficient evidence, however, to suggest that the size, density of packing, and hydration of the particles have great effects upon permeability. Bodman [6] has shown that textural differences exert little influence on permeability at very high apparent densities for soils finer than fine sandy loams. The permeability-rate was exceedingly slow at apparent densities greater than 1.4 to 1.5. A decrease in total porosity, however, does not always give a true picture of the reason for diminished permeability. The content and distribution of large pores that permit ready percolation of water is the important factor. In terms of the concept of Schumacher, the content of non-capillary pores determines in a large measure the percolation-rate of a uniform soil-column. Burger [7], for example, found that the infiltration-rate of various soils was closely correlated with the air-capacity or non-capillary porosity.

In defining non-capillary porosity in terms of the size of pores that do not hold water tightly by capillary forces, it is obvious that the tension under which a soil is drained will affect the relative amount of the so-called non-capillary pores. Under most conditions the soil is saturated and allowed to drain under gravity. Recent experimental evidence [8], which has been obtained in studies of the relation of soil-permeability to the nature of the pF-moisture curves, indicates that permeability is definitely related to the shape of these curves. In the first place, the amount of water that is withdrawn from zero-tension to the tension of the flex-point of the curve appears to be closely associated with the rate of water-movement through the soil-column. This amount of water represents the pores that are rather easily drained and are usually filled with air; they may be called the non-capillary pores. The larger the amount of these pores, the greater is the permeability. Secondly, the tension of the flex-point in the pF-moisture curve seems to exert an appreciable effect upon permeability. The lower the pF of the flex-point, the greater is the permeability. This simply suggests that the size of the pores are larger as the tension necessary to drain them is smaller.

These two characteristics are well illustrated in the change in permeability of a sample of Cecil clay upon compression. This soil was compressed so that there was 13 per cent more soil per unit-volume. The loose soil had a constant percolation-rate of 127 cc per 10 min; the rate of the compressed soil was 5.8 cc. Compression raised the pF of the flex-point from 1.65 to 1.80; it decreased the so-called non-capillary porosity from 12 to 5.5 per cent of the total soil-volume. The primary effect of compression was to change the nature of the pores; it caused a decrease in the amount and size of the larger pores as evidenced by an increase in the tension of the flex-point as well as a decrease in the water withdrawn from zero-tension to the tension of the flex.

The effect of increasing the tension of the flex-point on permeability at a constant porosity may be illustrated with various grades of sands. For example, 20- to 40-mesh sand was found to have a percolation-rate of 1,216 cc per 10 min; the pF of the flex was 1.25. On the other hand, 40- to 60-mesh sand had a percolation-rate of 675 cc per 10 min; the pF of the flex was 1.50. Two soils that drain at about the same pF will have different permeabilities dependent upon the content of the larger pores. For example, a Genessee silt-loam, with a non-capillary porosity of 14.7 per cent, exhibited a percolation-rate of 205 cc per 10 min; an Iredell sandy clay-loam, with a non-capillary porosity of 9.2 per cent, had a percolation-rate of 36 cc per 10 min.

If one assumes that the permeability of a soil-column should vary directly with the content of large pores and inversely with the tension necessary to drain these pores (which more or less establishes their average size), a high degree of correlation is obtained between the measured and calculated permeabilities. Observed permeability increases exponentially with the ratio (content of large pores/pF of the flex). It has been found that this relationship holds for such widely varying materials as sand, zeolite, clays, and soils in their natural structure. In other words, soil-permeability is dependent upon the non-capillary porosity, if the tension at which this porosity is determined is properly chosen. Evaluation of the effective pore-space from moisture-tension curves appears to offer considerable promise for characterizing the constant in the Darcy equation more accurately in terms of soil-properties.

Donat [9], Bradfield [10], and others have studied means for calculating the size-distribution of pores in the soil as means for characterizing the soil pore-space. The results of further research in this direction will undoubtedly provide a much clearer understanding of porosity in soil-permeability problems.

In thinking of the permeability of the soil-profile, one is immediately confronted with the realization that the porosity and permeability of the various layers may be greatly different. In a saturated soil, the percolation-rate through the profile is determined by the permeability of the least pervious horizon. This fact was demonstrated by Wollny in 1885 who showed that one

cm of loam placed in the middle of a 50-cm column of sand reduced the permeability of the entire column from 10 to 50 times, depending upon the size of the sand-fraction. If such an impermeable layer exists in the subsoil, water- or air-movement of any consequence through such an horizon can only take place through cracks, fissures, old root-channels, or worm-holes. Often, the permeability of the entire profile may be limited by a shallow impermeable layer at the immediate surface.

The movement of water in the larger pores may be influenced considerably by the resistance of entrapped soil-air. If water that enters the soil leaves pores that are in contact with the atmosphere, the soil-air pressure remains unchanged. However, if a rapid entrance of water into the soil entraps appreciable quantities of air, the soil-air pressure will retard water-movement.

Aeration and soil-porosity

Soil-aeration implies both the air-capacity of soils and the ease of renewal of the soil-air from the atmosphere. Aeration is closely dependent upon the texture and structure of soils. Sandy soils contain many large pores; they have too much aeration at the expense of an adequate water-holding capacity. Clays, on the other hand, have rather low air-capacities. Sufficient aeration is one of the major problems for good plant-growth on such soils. If the individual clay-particles are closely packed together, there are no large pores for aeration.

The air-capacity, or non-capillary porosity of the surface-soil is a very dynamic property. It changes with weather-conditions and the frequency of tillage. Tillage-operations usually increase the total porosity and air-capacity of a compact soil. On the other hand, extreme pulverization and rolling may lead to a decrease in non-capillary porosity. The impact of rain-drops on a granular, well-aerated soil tends to disperse the soil-particles and causes a compaction of the immediate surface. This reduction of porosity is responsible for poorer aeration, reduced bacterial activity, and a lower infiltration-rate for precipitated water. Under special conditions of excessive packing, when the soil is wet, the air-capacity may be reduced to almost zero.

Kopecky [11] has proposed the following air-capacity ranges for the optimum growth of several farm-crops: Sudan grass, 6 to 10 per cent; wheat and oats, 10 to 15 per cent; barley and sugar beets, 15 to 20 per cent. It is fairly well established from practical experience that these crops are arranged in correct order as far as their relative needs for aeration are concerned. Yoder [12] obtained the highest yield of seed-cotton in artificially prepared seed-beds when the non-capillary porosity was over 30 per cent. Other investigations have indicated that the non-capillary porosity of the seed-bed is an important factor in successful crop-production. Recent experiments with the growth of sugar-beets on heavy clay-soils of northwestern Ohio have indicated tenfold increases in the yield of beets as the air-capacity was increased from about two to eight per cent. When the air-capacity is small there is insufficient oxygen within the soil for the roots of plants to carry on normal respiration-activities. Consequently, root-development into oxygen-deficient layers is usually restricted.

Doiarenko showed that the size of the granules is an important factor in regulating the non-capillary porosity or air-capacity of soils. Granules smaller than 0.5 mm in diameter only gave an air-capacity of 2.7 per cent by volume, whereas 1.0- to 2.0-mm granules gave an air-capacity of 29.6 per cent. The oxygen-content of the soil-air increased similarly with the non-capillary porosity.

The renewal of soil-air--Most of the present data on the composition of the soil-air indicate that the amount of CO_2 and O_2 does not vary much within the immediate surface. There may be some question, however, as to the applicability of these data to all soil-conditions, especially to rather impervious soils. Nevertheless, in light of the intensity of CO_2-production through plant-growth and micro-biological activities, the apparent lack of any large accumulation of CO_2 in the surface-soil suggests a rapid exchange of gases with the atmosphere.

Although such meteorological factors as temperature and barometric changes as well as wind- and rain-action exert some influence upon the renewal of soil-air, the major cause of air-exchange between soil and atmosphere is through the process of diffusion. Buckingham [13] was one of the first investigators to apply the kinetic theory of the diffusion of gases to soil-aeration. He applied the term 'diffusion-constant' to designate the rate of movement of gases through the soil pore-space as a result of kinetic movements. He studied the diffusion of air and CO_2 through the layers of various soils at different moisture-contents and also measured the transmission of air and CO_2 through these same layers under small pressures. A definite correlation was observed between the diffusion-constant and the free pore-space (total pore-space not filled with water). The addition of water to the soil-layer caused large decreases in the rate of diffusion. These

results confirmed the earlier findings of Hannen [14] who showed that the sum of the cross-sectional area of the effective pore-volume was the most important factor affecting the diffusion of CO_2.

On the basis of his data, Buckingham expressed the relation of the diffusion-rate to the free pore-space by the equation

$$D = kS^2 \tag{3}$$

where D is the diffusion-constant, S is the free pore-space, and k is a proportionality-factor or diffusion-coefficient; k was calculated to be 2.16×10^{-4}. This expression points out that the rate of diffusion is reduced to 1/4 as the free pore-space is reduced to 1/2. It is interesting to note that a free pore-space of one gives a diffusion-constant of 2.16×10^{-4} for the free diffusion of CO_2 and air, a value which approximates very closely the determined value of 2.20×10^{-4}.

Apparently, the only controlling soil-factor on the rate of diffusion is the free pore-space, since the nature, texture, structure, and moisture-content of the soil do not materially affect diffusion only as the pore-space is altered. Diffusion is a continuous process as long as the free pore-space does not become zero. Changes in the free pore-space may result from compaction or saturation of the pores with water. Hannen [14] found that the diffusion of CO_2 through kaolin and a powdery loam was diminished as much as 40 per cent by compaction. He also observed that moistening sands to 40 per cent of their total water-holding capacity resulted in about a 40 per cent decrease in the rate of diffusion.

Romell [15] has interpreted the data of Hannen and Buckingham as showing that the high water-holding capacity (low non-capillary porosity) of fine-textured soils restricts the diffusion-process considerably under natural conditions. He has suggested that the diffusion-coefficient may be lowered from 1/2 to 1/3 of that for free diffusion. Moreover, he has emphasized the importance of a compacted layer at the immediate surface on reduced aeration.

Permeability of soil to air--Since diffusion-processes apparently account for most of the normal aeration of soils, one should expect a close relationship between the soil-factors affecting the rate of diffusion and the factors that determine the permeability of soils to air. The importance of air-permeability as a physical characteristic of soils was recognized as early as 1879 by Renk [16], Ammon [17], and Wollny [18]. They showed that permeability increased with the amount and size of the soil pore-space. For example, Renk found that a coarse sand with a total pore-volume of 55.5 per cent was 1000 times more permeable to air than a fine sand with a pore-volume of 37.9 per cent. The larger pores in the coarse sand were far more effective for air-movement. Permeability was greatly lessened by the presence of water in the pores. These findings were later confirmed by Wollny who showed that the presence of a small impermeable layer in the soil-column greatly decreased the permeability.

Buckingham [13] determined the permeability of the soil for CO_2 and air under small pressures and found that the permeability-constant was proportional to about the sixth or seventh power of the free pore-space. More recent investigations by Buehrer [19] on the flow of air through columns of lead-shot have indicated that permeability varies directly as the square of the average diameter of the particle. Experiments on sand-clay mixture have shown that only a small amount of clay is necessary to restrict air-movement through the system. The effective diameter of the pores between the sand-grains is quickly reduced by the clay-particles. Buehrer observed that air-permeability is not a linear function of porosity and has suggested that a large portion of the pore-spaces between the solid particles do not contribute to the passage of air because of resistance to air-flow.

Most of the experimental evidence seems to suggest that the factors of porosity that limit air-permeability are similar to those affecting water-movement. The amount and size of the larger pores appear to be of great importance.

The permeability of a given soil-column decreases rapidly with the depth of the column. Renk observed that the volume of flow through sand-columns was inversely proportional to the depth. A similar relationship was obtained by Buehrer. A significant feature of Buehrer's data is found in the large decrease in the rate of air-flow through fine-textured soils after the depth exceeds about two to five cm. These results, along with the restricted air-movement under compact conditions, suggest that the present of an impermeable layer at the soil-surface may affect soil-aeration to a greater extent than is usually realized.

Summary

The amount, size, and continuity of the soil-pores greatly affect the water- and air-relationships of soils. Capillary conductivity decreases as the size of the pores between the particles becomes smaller. On the other hand, if the pores are so large as to prevent the formation of continuous films throughout the soil-mass, capillary conductivity will be small.

The permeability of the soil to air or to water under conditions of saturated flow is undoubtedly determined by the amount and size of the pores, particularly the larger pores that drain under rather low tensions. The so-called non-capillary pores are primarily responsible for soil-aeration as well as for rapid water-movement under gravitational influences. More research is needed, however, to characterize the significance of these larger pores in soil permeability-problems.

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DISCUSSION

ALFRED B. C. ANDERSON (University of California)--When there is a vertical component of the flow of water and when the variation in solute concentration is important, it is desirable to introduce a more general mathematical function representing the energy of the water than the capillary or pressure-potential ψ. If the function called "free energy," f, is used in place of ψ, many more useful relations can be developed relating the behavior of water (whether as

soil-moisture, free water, vapor, ice, or even plant-sap [see 1, 2 of "References" at end of paper] to its energy-content. The use of the free-energy function also facilitates the treatment of problems involving temperature as a variable.

If f = the specific free energy, e = the specific internal energy, v = the specific volume, s = the specific entropy, P = the pressure and T = the temperature of the water, we have the well-known expression

$$f = e - Pv - Ts \tag{1}$$

which, when we are considering changes Δf in the free energy, becomes with the aid of the first and second laws of thermodynamics,

$$df = -sdT + vdP - dw_m \tag{2}$$

where dw_m represents the total work dw done by the system minus the work of expansion Pdv against the pressure P. That is

$$dw_m = dw - Pdv \tag{3}$$

The function f, invented many years ago in the field of thermodynamics, includes many more characteristics useful not alone in the study of soil-moisture, but also in the study of the more complex system composed of the soil, moisture, and plant [2] where the potential-function is entirely inadequate.

As used in previous soil-moisture literature, the total potential has properties analogous to the function we now introduce as the total specific free energy f: The total potential of moisture equals the sum of the osmotic potential, the capillary or pressure-potential, and the potential due to the presence of the water in a force-field. The total specific free energy of the water in any state equals the sum of the component Δf_O of the total free energy due to osmotic pressure caused by the presence of dissolved material; the component Δf_P of the total free energy due to hydrostatic pressure; the component Δf_F of the total free energy due to the presence of the water in a force-field, as well as any other components of the total free energy that might affect the energy of the water.

Some of the more important characteristics of the free-energy function are presented below. Although the following conclusions will apply in general to other pure substances, we shall state them with special reference to water.

(1) When water exists in several states or phases, simultaneously in equilibrium with each other, the specific free energy Δf of the water is the same in each of the states. For example, when water in a salt-solution is in equilibrium with its vapor and ice, the specific free energy of the water is the same in all three phases. The equality of the specific free energies of the water in two or more phases describes the state of their equilibrium.

(2) The absolute or total value of the specific free energy f as defined above is never measured in practice. Only differences or changes in the function are measured (as is true of all potentials). For example, in the case of gravitational potential, we never measure its absolute value at a point but rather its value with respect to some datum such as sea-level. Likewise, we do not measure the absolute value f of the free energy of water, but instead its value Δf with respect to some datum which is usually taken as a body of pure free water at the same temperature and pressure. Unlike potential though, it is possible to calculate the absolute free energy f, but it is usually of little practical importance.

(3) If the changes of state of the soil-moisture (from a state A to a state B) are carried out at constant temperature and pressure, we have for finite changes

$$\Delta f = f_B - f_A = -\int_A^B dw_m \tag{4}$$

Thus the free energy Δf of water in the state B with respect to the state A (which might be chosen as the datum) is equal to the work that must be done on the water (at constant temperature and pressure, and neglecting the work of expansion against the pressure P) to bring it from the datum A to the state B. That is, the change in free energy in any transformation of a system in going from a state A to a state B equals the mechanical work required to go from A to B (at a constant temperature and pressure, and neglecting the work of expansion against the pressure P).

If we consider a closed system in which spontaneous changes or movements of the water are taking place, we find that the change in the free energy is always such that

$$\Delta f < 0 \tag{5}$$

That is, in all spontaneous changes of moisture in nature, the free energy tends to decrease. This is also true of the potential of soil-moisture. For example, wet soil can be shown to have a higher free energy than dry soil (both free energies are, of course, negative with respect to a free pure-water surface used as datum). Thus if we combine the two soils in a closed system, we should expect, according to the above, that the sum of the free energies in the system composed of both the wet and dry soil would spontaneously decrease. This is accomplished by moisture flowing spontaneously from the wetter soil where the free energy is greatest to the drier soil where the free energy is least. Of course, the free energy of the wetter soil would decrease and the free energy of the drier soil would increase, but the net free-energy change for the whole system would be a decrease.

If we have a number of interconnected regions of moisture (each having a different total free energy Δf) in a closed system, the Δf of all regions will tend to approach the same value. If the interconnections are through the vapor rather than through the liquid phase, distillation will continue until enough moisture has moved from regions of high Δf to regions of low Δf to make the value of Δf uniform throughout. Whether the water is liquid ice, or vapor, moisture will always move from regions of high Δf to regions of low Δf until the value of Δf is uniform throughout.

(4) In analogy with the idea of potential as used in electricity, magnetism, and soil-moisture studies, the gradient of the total specific free energy in the soil is the negative of the force F (per gram of water) acting on the water. That is

$$F = -\text{Grad}\,(\Delta f) \tag{6}$$

(5) The dependence of the total specific free energy Δf of moisture on its vapor-pressure p is given by

$$\Delta f = RT \log\ (p/p_0) \tag{7}$$

where p_0 is the vapor-pressure of the datum (usually pure free water). This provides a dependable way of determining the total free energy of water in any state whether as soil-moisture or as plant-sap. The total specific free energy Δf may be composed of a number of partial specific free energies, the more common of which are given below.

(6) The dependence of the free energy Δf_p of water on the hydrostatic pressure ΔP as measured by its freezing-point depression ΔT is given by

$$\Delta f_p = (v\ell\Delta T/T\Delta v) \tag{8}$$

where ℓ is the heat of fusion and Δv, the change in specific volume per gram when water freezes. Expressed in terms of hydrostatic pressure ΔP, it is

$$\Delta f_p = v\,\Delta P \tag{9}$$

(7) The dependence of the free energy Δf of water on the amount of dissolved material as measured by its freezing-point depression ΔT is given by

$$\Delta f_o\ \ell\Delta T/T \tag{10}$$

Expressed in terms of the osmotic pressure ΔP_o, it is

$$\Delta f_o = -v\,\Delta P_o \tag{11}$$

(8) If the area of a water-air interface changes by the amount ΔA, the free energy of the water changes by the amount

$$\Delta f_\sigma = \sigma\,\Delta A$$

where σ denotes the surface-tension of water.

(9) If a particle of water is moved from a point A to a point B in either a gravitational field or an adsorptive field F, surrounding a soil-particle, the change in the free energy Δf_F of the water is given by

$$\Delta f_F = \int_A^B F \cos \Phi \, dx \tag{12}$$

where dx is an element of the path taken between A and B and cos Φ is positive if F and dx are in opposite directions.

(10) The total free energy Δf of soil-moisture may be expressed as the sum of a number of partial potentials.

$$\Delta f = [\Delta f_p + \Delta f_\theta + \Delta f_\sigma + \Delta f_F + (\text{any other partial free energies that might contribute to } \Delta f)] \tag{13}$$

According to Darcy's equation, which is founded on experiment, the velocity of flow of a liquid is

$$V = - KF \tag{14}$$

where F is the force per gram of water (in the capillaries) causing movement of the moisture in the capillaries. Substituting equation (13) into equation (6), and taking this result and substituting into equation (14), we have

$$V = - K \text{ Grad } (\Delta f) \tag{15}$$

The velocity of flow of the moisture V in equation (14) is also the quantity of flow (per unit cross-sectional area in the tube of flow) per second, past any point in the tube of flow of the moisture. The meaning attached to V above is also the meaning that must be attached to Q in equation (1) given by Baver so that Baver's equation might rather have been written

$$V = - K \text{ Grad } \psi \tag{16}$$

Equation (15) should replace equation (16) because the former is far more general than the latter which deals only with the capillary potential.

The pressure or capillary potential, as customarily used in the past, does not consider the effect of variation in the concentration of dissolved material in producing water-movement. The capillary or pressure-potential explicitly deals only with the energy in the soil arising from the mechanical tension or pressure existing in the soil-moisture. Tensions and pressures are not the only factors that cause movement of soil-moisture. Gradients of solute concentrations, when present, are equally effective in soils and plants producing moisture-movement. If the moisture-content is uniform in a homogeneous soil, there will still be water-movement if there is a gradient of solute concentration. The use of the total free energy in equation (14) predicts this, but the capillary potential in equation (14) does not.

(11) By using the free-energy function, the dependence of the energy of the moisture on temperature can be determined [see 1 of "References" at end of paper]; the energy of soil-moisture in the field at different moisture-contents can be calculated from freezing-point measurements carried out with a dilatometer [1, 3]; and the movements of moisture from the soil into the plant and up to the tops of even the highest trees is explained [2].

For these reasons, we believe that the use of the free-energy function in place of capillary potential gives much more promise for all studies where any energy-relations involving soil, moisture, and plants are concerned. Potential was developed in the fields of electricity, magnetism, and mechanics and is admirably suited to these, but is inadequate when used in describing the movements of moisture in the soil and to the plant. Gravitational potential, pressure-potential or capillary potential, and electric potential are very special cases of the general function called free energy.

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G. B. BODMAN (University of California)--The equation $Q = - K \text{ Grad } \psi$ as a general expression of the rate of capillary flow of water through soils is not strictly correct. The water in moist soils at any degree of saturation is affected by all forces acting upon it and its direction and velocity of movement are controlled, for a given conductivity, by the resultant of all such forces. In soils unsaturated with water the gradient of ψ is frequently of such magnitude that the gravitational force cannot be ignored, no matter in what direction flow occurs. For these reasons "Grad ψ" should read "Grad Φ" where Φ represents the total potential. It seems highly desirable to emphasize that the underlying concepts of fluid flow may be applied to water-movement in soils at all degrees of wetness and under positive pressures, even though agricultural interest is greatest when the water-content lies somewhere between saturation and "field-capacity."

It is not believed that the usual observations that the rate of rise of capillary water is much faster in sandy than in clayey soils can be taken as evidence of the reduction in capillary conductivity with size of soil-pores. Capillary-rise data published by E. W. Hilgard [1] leads to contradictory conclusions with respect to rate of rise for the same two columns of "0.12-mm sand" and "clay," namely, (a) that the average rate of rise is greater in the sand than in the clay and (b) that the average rate of rise is greater in the clay than in the sand. The apparent anomaly is explained by the choice of time-ranges over which the average rate of rise is computed. The usual capillary-rise experiments have been made under conditions such that only two exact observations besides those concerning gravity can be recorded. These are the position, outside of the moistened soil-column at which $\psi = 0$ (this is not always kept constant throughout the course of an experiment) and the average rate of rise of the margin of a visibly wetted soil. The latter decreases so rapidly with time that it is of little significance unless the entire experiment is greatly modified. No conclusions based on the fundamental flow-equation can be drawn regarding conductivity unless something specific is known concerning the driving force and the volume of flow.

The various experimental data concerning water-movement in unsaturated soils are in some respects difficult to interpret. The results obtained by Moore and cited by L. D. Baver have been given support in later experiments by Bodman and Marshall with soil-colloids of different grain-size and different pore-size distribution. There developed at the higher tensions, however, a tendency for the coarser and more aggregated colloid, which contained only about 20 per cent of pores having effective diameters less than 20 millimicrons, to exhibit similar conductivities to those for the finer and more highly dispersed colloid, which contained twice as great a volume of pores having the same upper limit of equivalent pore-size. In other words, the colloid of coarse pore-size failed to exhibit at pF = 2.1 the distinctly lower conductivity with respect to the colloid of finer pore-size, which it displayed between pF 2.1 and 1.0.

Numerous difficulties probably still exist in the rationalization of our knowledge concerning the more rapid flow which occurs in the water-saturated, or almost water-saturated, condition. Continuous flow for even relatively brief periods results in marked reductions in water-conductivity of laboratory-packed soil-columns which may, in turn, be succeeded by unpredictable fluctuations in permeability [2, 3]. Such changes also have been observed in the field [4]. Both physico-chemical and microbial influences may be responsible for these peculiarities. Alterations in the base-status of the soil-clays, which in turn affect the pore-size distribution within the soil-mass and the mobility of the clay-particles themselves such that pore-blocking may occur, cannot be overlooked in considering the general problem of soil-permeability. Such effects are well known to be conspicuous where flow of saline water is followed by that of salt-free water, thus inducing the maximum hydrolysis of the clay-particles. Recent experiments [3] in which severe alteration of the base-status of a soil was known to have been brought about by continuous percolation with saline water alone, however, have not demonstrated any alteration in conductivity to the saline water itself. Hydrolysis, dispersion, and pore-size reduction were presumably inhibited.

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R. GARDNER (Colorado State College)--I have been wondering recently if the conception of a soil as consisting of solid matter and pore-space occupied by air and water in varying proportions is an accurate conception when applied to some of our highly colloidal soils with a high sodium-content. When these soils are wet it seems to me that the condition is one in which the non-colloidal material is suspended in a colloidal jell with no true pore-space present and that the slight water-penetration is either due to dehydration of the jell as a result of moisture-tension or of flow through the jell. I suppose there is little difference so far as flow is concerned, in whether swelling of the colloidal material due to hydration has reduced the pore-space to a very low value or whether the pore-space has been replaced by a jell through which there is but very little movement.

W. GARDNER (Utah State Agricultural College)--I am interested particularly in Baver's discussion of the relation of the pore-space to the pF-moisture-percentage curve. It seems natural to presume that the configuration of the air-solid interface in the dry soil would determine the shape of this curve but I believe the converse is not necessarily true. In fact, it would appear to me that there are an infinite number of configurations that would correspond to a single curve.

We might consider a simple aggregation of spheres of uniform diameter. We would expect to obtain a curve resembling that for a soil and it would require the removal of relatively larger quantities of water to increase the tension when the aggregation is saturated than when it is comparatively dry, and a granular structure would not be required.

Of course when a soil is plowed with the moisture just right it does break up into granules, but I am somewhat inclined to the view that the manner in which it breaks up is determined largely by chance. Clark Affleck succeeded in building up a more or less successful empirical size-distribution curve for the soil on the basis of the theory of probability, and it seems to me that it would serve equally well to determine the manner in which the action of the plow breaks up the soil-mass into granules.

It could be urged of course that cleavage-surfaces intersecting in devious ways may have considerable influence on this granulating process and I should not wish to become definitely committed to the other point of view, although it does at present seem to me that chance has a lot to do with it.

C. V. GIVAN (University of California)--No mention is made in Baver's paper of conditions under which Darcy's law does not apply. A statement regarding these conditions is given by M. Muskat [1]. He points out that "it is safe to conclude that in the great majority of flow-systems of physical interest, the flow will be strictly governed by Darcy's law, except possibly in very localized parts of the porous medium of very limited dimensions." A Reynolds' number of 1, in which the length represents any reasonable average diameter of the granular material, appears to be a safe value of R below which Darcy's law applies.

Bakhmeteff and Feodoroff [2] not only present their own work but discuss a valuable review of work done on the flow of fluids through porous material which has been confined in tubes. They relate a friction-factor to a Reynolds' number and introduce what they call "reduced" characteristic parameters of void velocity and length in order to account for the effect of variations in flow through granular media.

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R. E. HORTON (Consulting Hydraulic Engineer, Voorheesville, N. Y.)--I have no criticism to make of the paper as a report of the Committee but wish that the whole subject of air in soils might have a thorough review. This question comes in rather critically in connection with the work of the Research Division of the Soil Conservation Service on infiltration, since it is evident that as water enters the soil through infiltration, air must either escape vertically through the same system of soil-pores or be either (a) displaced laterally or (b) compressed within the soil. Under natural rain-conditions it cannot be displaced laterally but may be so displaced in case of sprinkled-plat experiments. I have found little evidence of any appreciable degree of compression of air within the soil as regards its effect on infiltration. Would be glad to know if any such instances have been observed in this country.

M. R. HUBERTY (University of California)--The conclusions drawn from the work of Kopecky and Yoder might be in error in that it is assumed that differences in yield can be attributed to differences in air-content. When physical characteristics of a soil are altered there is usually an accompanying chemical change. Factors other than air might, then, be contributing to the differences in yield.

Since several references are given to field-conditions it would seem advisable to stress the influence of cultivation upon density of soil immediately below the stirred zone. The text leaves the impression that cultivation usually improves permeability. Many times the reverse condition is the case.

The influence of inorganic fertilizers upon soil-permeability has not been mentioned. This must be an important factor in some humid regions as it often is in arid sections. In the irrigated sections there is also the possible change in the physical characteristics of a soil resulting from applications of irrigation-waters of various chemical composition. Measurements made in check-plots near Wasco, California, indicate marked reduction in rates of water-penetration where ammonium sulfate or sodium nitrate had been applied in solution form to the entire surface of the soil in the plots. Water penetrated the soil in plots receiving sodium nitrate at the rate of 1500 pounds per acre at approximately 1/300 of the rate in the untreated plots. The irrigation-water was of low salt-content.

J. KITTREDGE (University of California)--The point is made that the non-capillary pore-space is important; and as these pores become larger, as in the case of worm- and grub- and gopher-holes, it would seem that the movement of water when the soils are saturated must more and more resemble its movement under the force of gravity through pipes, which in the case of soils will be of varying diameter and roughness. In hydraulics the discharge of pipes is generally supposed to be a function of the diameter or hydraulic radius and of a roughness or friction-factor. It may be that these factors should be suggested as of possible importance in the question of soil-permeability, although at the same time they will obviously not be easy to evaluate.

M. R. LEWIS (United States Department of Agriculture, Soil Conservation Service)--It seems to me that it would be well in the paper to make clear when the term "permeability" is used in referring to a specific characteristic of the soil, or, in other words, is synonymous with the term "conductivity" and when the word is used in the more general sense.

The fact that the overall permeability of a non-uniform soil-column is governed, at least to a very great degree, by the least permeable horizon is true, but the solution of field-problems, particularly in irrigation, may be dependent on the storage-capacity of the soil-profile above the tight horizon. Sometimes this capacity is so great that the permeability of the lower horizon is of no consequence in the rate of application of irrigation-water. The permeability of the lower horizon may still be of importance in determining the quantity of water which should be applied. Similar problems occur in the infiltration-problem as it applies to erosion-control practices.

In the first and fourth sentences (particularly the latter) of the last paragraph, before the summary, the inference seems to be that there is a sudden increase of resistance with column-lengths of two to five cm. The second and third sentences, on the other hand, give the generally accepted idea that the total resistance varies directly with the length of column.

O. W. MONSON (Montana State College)--It is suggested that it would be worth while introducing a paragraph to explain the factor pF more completely, especially since it is used rather freely in the rest of the paper, and since those not closely associated with the physics of soil-moisture are not familiar with the term. Attention is called to the practical importance of layers of low permeability in regulating the motion of air and water in soils. The question is also raised as to the interpretation of Dr. Baver's statement that the yield of sugar-beets increased tenfold by increasing the air-capacity of soils by about two to eight per cent. Presumably this refers to the increase, and not to the total air-capacity, since generally many irrigation investigators feel that the optimum conditions for growth require that approximately 50 per cent of the total pore-space be left open and that it not be occupied by water. It is thought that the presence of air in the soil is very important and it has been observed in Montana that over-irrigation has a tendency to reduce greatly the air-content of the soil and to puddle or settle the soil, in this way excluding a large amount of air from it; this is bound to have a considerable effect on the growth of crops.

R. E. MOORE (University of California)--The study of the permeability of soils to gases and water as it is related to the pore-space and the size-distribution of pores should be very fruit-

ful. Such a study should lead in time to a more fundamental definition of pore-types than we now have. Such terms as "capillary" and "non-capillary" pores are not adequately defined at the present time.

The flex-point of curves of pF = f (moisture-content) is probably very closely related, if not identical, to the point at which the capillary permeability of soil becomes zero, to the moisture-content and pF of soils at field-capacity, and to the moisture-content and pF of some medium textured soils at the moisture-equivalent. This suggests that some quantity analogous to the flex-point might be determined for soil in situ in conjunction with the field-permeability or infiltration-rate. The field-capacity and its pF, along with real apparent density, and total pore-space of the soil in situ might be used in conjunction with the infiltration-rate to derive the porosity-factor described by Baver [L. D. Baver, Soil permeability in relation to non-capillary porosity, Soil Sci. Soc. Amer. Proc., v. 3, pp. 52-56, 1938].

G. W. MUSGRAVE (U. S. Department of Agriculture, Soil Conservation Service)--The effect of porosity upon water-movement to a certain extent also acts in reverse. Water-movement into and through soil has certain definite effects upon porosity. Among these effects are the following:

(1) Mechanical disintegration of soil-structure and particularly of aggregates--The cases which represent extreme conditions are (a) those in which aggregates slack readily upon the addition of water, and (b) those in which aggregates are relatively stable in water. The former condition is very common in soils which have been subjected to intensive tillage, while the latter is very common in virgin lands, pasture-lands, forests, etc. Given two soils of like initial porosity, one of which has been intensively cultivated (and has been recently plowed or cultivated), while the other has been in grass or forest, the application of rain or water will commonly show a rapid decline of infiltration-rate in the former, and a much more gradual decline in the latter, largely because of reductions in porosity of essentially similar rates.

(2) The swelling of colloids and constriction of pores--From soils of low colloidal content to soils of high colloidal content, the entire range of these phenomena are exhibited. There appears to be wide differences also, not only in the rate of swelling of different soils under similar changes in moisture-content, but also wide differences in rate because of differences in time required to secure sufficient intake of water to cause maximum swelling. A clay-loam which received applications of water at two inches per hour for three hours on each of four successive days (under conditions where free runoff was permitted), was found to be insufficiently wetted at an eight-inch depth to cause appreciable swelling.

(3) Water contained within pores--Obviously the effectiveness of porosity upon the movement of water is greatly affected by the amount of space already occupied by contained water as well as by energy required to move it. This phase of the problem is amply treated in the paper for discussion.

O. R. NEAL (U. S. Department of Agriculture, Soil Conservation Service)--The point made concerning the differences in porosity and permeability of different layers within the same profile is of considerable practical significance. In lysimeter-investigations at this Station runoff, percolate, and vapor-loss have been measured for two soils which differ widely in non-capillary porosity.

The Marshall silt-loam has a total porosity of about 55 per cent and a non-capillary porosity of 25 per cent of the soil-volume throughout the surface three feet. In the Shelby silt-loam the total pore-space varies from 45 per cent in the surface to 30 per cent at a depth of three feet. Of this amount, the non-capillary pore-space accounts for approximately ten per cent of the soil-volume in the surface-foot and five per cent of the soil-volume below that depth.

The runoff from the cultivated surfaces of these small areas has not been significantly different for the two soils under precipitation-conditions of recent years. The cultivation-operation doubtless increases the non-capillary pore-space of the surface-layer appreciably. Despite the lack of difference in runoff, the percolate, at a depth of three feet, has been four to five times higher from the soil having the greater porosity. The water held in the surface-layer of the Shelby soil is presumably unable to pass down through the available pores rapidly, and is thus subject to greater loss in a vapor-form. If several large storms were to occur within a short period, a considerable difference in runoff from these two soils would be expected.

In estimating soil-permeability on the basis of the non-capillary porosity indicated by moisture-tension curves, it seems possible that a time-element might be involved. It is conceivable that two soils of different structure might yield the same amount of water when changed

from zero-tension to a stipulated pF-value, but that the time required to reach equilibrium would be appreciably different. The permeability of the two soils to air and water would be expected to show a corresponding difference. Since the time-element is so intimately involved in infiltration under field-conditions, it seems that this point may deserve some consideration.

L. B. OLMSTEAD (U. S. Department of Agriculture, Bureau of Plant Industry)--He refers to surveys in which are given the volumes of soil, water, and air at the normal moisture-capacity for laboratory-packed samples of profile-layers of 11 erosion-experiment-station soils, and states that these are the capillary and non-capillary porosity of the materials, not at a single pF but at the capillary tensions developed by the wet soil-material in contact with a dry soil-layer [L. B. Olmstead, Some moisture relations of the soils from the erosion experiment stations, U. S. Dept. Agric. Tech. Bull. 562, 1937].

L. A. RICHARDS (U. S. Department of Agriculture, Bureau of Plant Industry)--The Darcy law has been variously quoted and paraphrased in the literature and often incorrectly. The variance in these quotations may perhaps be traced to the original statement of the law. H. Darcy, on the basis of his observations on water moving vertically through horizontal beds of filter-sands summarized his findings as follows [Les fontaines publique de la ville de Dijon, Paris, 1856]:

> "Ces expériences démontrent positivement que le volume d'eau qui passe à travers une couche de sable d'une nature donnée est proportionnel à la pression et en raison inverse de l'épaisseur des couches traversées; ainsi, en appelant $\underline{s}$ la superficie d'un filtre, $\underline{k}$ un coefficient dépendant de la nature du sable, $\underline{e}$ l'épaisseur de la couche de sable, $P - H_0$ la pression sous la couche filtrante, $P + H$ la pression atmosphérique augmentée de la hauteur d'eau sur le filtre; on a pour le débit de ce dernier $Q = (ks/e)(H + e + H_0)$, qui se réduit à $Q = (ks/e)(H + e)$ quand $H_0 = 0$ ou quand la pression sous le filtre est égale au poids de l'atmosphère."

One interpretation of his introductory statement would be that the flow-rate is proportional to the pressure-difference. This of course is not generally true. Soil-moisture-flow experiments are frequently carried on in the laboratory under the condition of zero-pressure difference and zero-pressure gradient. The final equation given above however removes this ambiguity and makes clear that the flow is proportional to the difference in what is commonly called the static hydraulic head, thus taking gravity-force into account. Unfortunately, there are numerous instances in the literature where the flow-equation has been expressed in terms of pressure-difference, the authors not realizing, and in some cases not being open to conviction, that in this form the flow-equation holds strictly only for the limited case of horizontal flow.

The flow-equation given by Baver, for example, is for the limited case of horizontal flow. For the general case of flow in any direction the h in his equation (2) should represent hydraulic head and not pressure-head. The limitation in the form of the law given may or may not have been accidental. His v, of course, should represent cubic centimeters "per square centimeter" per second.

It is becoming increasingly apparent that the permeability of soil is one of its most important physical properties and the study of soil-permeability is making the transition from a qualitative to a quantitative stage. It should facilitate progress for both scientific investigations and engineering applications if a unit for soil-permeability could be found that would be generally acceptable. Since many more permeability-studies will be made in the future than have been made in the past, we should not hesitate to choose a new unit if this seems desirable. This unit should be chosen so that it can be used for expressing the flow of any homogeneous liquid through any isotropic porous medium. Unfortunately the possibility of getting workers in various fields to agree on the use of such a unit seems slight. It may be possible, however, to designate a unit that will be generally acceptable to agronomic soil-workers and have the same unit at least second choice in other fields.

The Soil Physics Section of the Soil Science Society of America is sponsoring effort toward the selection and acceptance of such a unit and the cooperation of all interested persons and organizations is invited.

A new unit of permeability will here be unofficially and tentatively defined and presented for the sole purpose of provoking discussion and encouraging analysis and comparison of the units now in use. The new unit will be called the dar and the flow-equation used for its definition may be written in various forms such as

$$v = (Q/A) = -K(\mu_s/\mu)\nabla\Phi = K(\mu_s/\mu)\ gI = K(\mu_s/\mu)[g - (1/d)\nabla p]$$

where k is the permeability of the porous medium in dars, Q is the volume of liquid crossing the area A in the porous medium in unit-time, V is the flow-velocity, μ_s is the viscosity of water at 68°F (20°C), μ is the viscosity of the liquid, g is the acceleration of gravity, I is the hydraulic gradient, ∇ is the gradient-operator, Φ is the sum of the gravitational and pressure potentials, p is the pressure of the liquid, and d is its density. These, of course, are vector-equations and the negative sign is a matter of convention which need not be discussed here.

Consistent with the above equations, we may set down the following alternative word definitions for the dar:

(1) A porous medium has a permeability of one dar, if, for unit potential-gradient, unit-volume of water at 68°F crosses unit-area in the porous medium in unit-time.

(2) A porous medium has a permeability of one dar if unit hydraulic gradient and unit gravitational force per unit-mass produce unit-velocity for water at 68°F.

(3) A medium has a permeability of one dar if unit-water moving-force per unit-mass produces unit-flow velocity for water at 20°C.

(4) The permeability of any medium to any liquid, expressed in dars, is equal to the volume of the liquid crossing unit-area in unit-time per unit of potential-gradient multiplied by the ratio of the viscosity of water at 20°C to the viscosity of the liquid.

The foregoing expressions apply, of course, only under conditions where Darcy's law holds and it is assumed that consistent length- and mass-units are to be used in any given case.

Since the viscosity of water at 20°C is .01005 poise it is permissible to a sufficient approximation for most work to make numerical calculations as follows:

(5) The permeability of any medium to any liquid, expressed in dars, is numerically equal to the liquid flow-velocity per unit of potential-gradient per centipoise viscosity.

To the same approximation for numerical calculations where horizontal flow through test-specimens is involved, we have:

(6) The permeability of a porous medium expressed in dars, is numerically equal to the mass of the liquid crossing unit-area in unit-time per unit pressure-gradient per centipoise viscosity.

The dar, as defined, has a number of advantages. It has the dimensions of time and would be expressed in seconds when the second is taken as the time-unit. Thus it is suitable for international use and the numerical value for the permeability of a given porous medium when expressed in dars will be the same whether metric or English or any other standard length- and mass-units are consistently used in the measurement. It is suitable for work of high or low precision. The tremendous range in permeability often makes high precision unnecessary so that for much work dealing with water-flow it is permissible to omit the viscosity-ratio from the flow-equation. This can be done without changing dimensional relations. On the other hand, the dar is suitable for work of high precision where small viscosity-changes cannot be ignored and where liquids other than water are used. The dar may likewise be used for expressing the permeability of porous media to gases. Measured values of permeability may be expressed in convenient numbers by use of the sub-units millidar and microdar.

All persons interested in the problem of selecting a permeability-unit for agronomic and engineering soils-work are invited to send the writer their comments and views. These will be edited and properly acknowledged in a more complete review of the problem which is being prepared. It should be emphasized again that the dar-unit is presented here merely as a basis for discussion to bring out some of the points to be considered, and is not to be understood as a recommendation.

L. K. SHERMAN (Consulting Engineer, Chicago, Illinois)--My present interests in hydrology are with the Committee on Infiltration. The phenomena of infiltration are closely allied in almost all phases to the physics of soil-moisture.

In our work on infiltration, we invariably express the rate of infiltration in inches per hour, instead of the smaller units used in soil-physics. I presume that we would find very close coordination of the results in our work with the laboratory-work presented by Baver, if the units were referred to a common basis.

For scientific purposes, it is desirable to segregate the various phenomena into their individual amounts. In the derivation of infiltration from runoff on natural basins, we find that the stratification or soil-profile introduces so many local effects that it is quite impracticable to segregate concordant phenomena. Baver does not mention one important phenomenon in relation between soil-moisture and water-content, that is, the effect of colloids after the period of initial wetting.

F. B. SMITH (University of Florida)--Certainly organic matter and other factors conditioning soil-structure and porosity may have a marked influence on the permeability of the soil. While permeability of the soil may limit microbiological action, may not the microorganisms also influence permeability?

I am still of the opinion that Hannen's methods did not permit of any very definite conclusions regarding the diffusion of carbon dioxide through soils. Also if Buckingham could have eliminated certain sources of error in his measurements, no doubt he would have found a different relationship between soil-porosity and the diffusion of gases through soils. Possibly the diffusion of gases through the soil is not a linear function of porosity but I am of the opinion that some of the data indicating other relationships are questionable.

R. E. STEPHENSON (Oregon State Agricultural College)--I wish to suggest that some attention should be given to fundamental reasons for differing infiltration-capacities of similar soils under different systems of management. Why should organic materials that are added to the soil sometimes result in so marked an increase in infiltration-rates? Or why should there be so much difference in infiltration-rates with different plant-covers and fallow lands? Just what are the soil-changes brought about and can a quantitative measure be used to evaluate these changes?

The method of measuring or determining infiltration-capacity needs considerable study. Infiltration-rates, of course, vary with soil, depth, presence of interfering horizons, duration and intensity of rainfall, and amount of moisture in the soil at the time the infiltration-rate is determined. How may the method of measurement adequately evaluate such factors?

Adequate evaluation of infiltration-data will doubtless require a better understanding of soil-structure. Soil-structure to date has been rather elusive of measurement. It seems necessary to distinguish between natural soil-structure, and what might be called cultural soil-structure. For example, the natural structure of a laterite such as is found in the Nipe Soil Series, may give the Nipe soil a very high infiltration-capacity. This high infiltration-capacity may persist in spite of any tillage-practice. On some other soil, only the best practices, such as humus renewal with sod-crops, and the growing of legumes with fleshy, deeply-penetrating roots, can keep the soil sufficiently open to assure good water-penetration. Reasonably-good infiltration of water may depend nearly entirely upon the maintenance of satisfactory soil-structure by management practices. On some other soil, perhaps no management system will assure good water-penetration. These are fundamental soil-differences, not only to recognize, but to be measured.

C. A. TAYLOR (U. S. Department of Agriculture, Soil Conservation Service)--Measurements have been made of the compaction of soil in citrus orchards and of the influence on infiltration-capacity. The compaction due to traffic in the orchards and to cultivation-practices influences capillary conductivity as well as free downward movement due to gravity. Measurements of rates of absorption of water from irrigation-furrows [see 1 of "References" at end of discussion] showed that infiltration-capacity had been reduced by compaction to one-third that of soil which was shielded from traffic and cultivation.

Tests on the degree of compaction of soil in citrus orchards [2] showed the layer of greatest density was seven to eleven inches below the soil-surface. Additional data on field-measurements of compaction and its effect on infiltration have been reported [3].

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R. P. THOMAS (University of Maryland)--There is one point which you seldom see mentioned in regard to soil-moisture that I think is of considerable importance. Very little consideration has been given to the affinity between the capillary moisture and the soil-particle. If it were not for this affinity we probably would have much less capillary moisture and a much higher non-capillary porosity in the soil. Using the examples which Baver cited, the Genessee soil wets very rapidly and Iredell wets rather slowly. In a recent conversation with some of the workers of the United States Department of Agriculture they stated that the mineral and physical make-up of these soils were practically the same although the slight change in the mineral make-up of Iredell had little if any affinity for water. Evidently this attraction between the soil-particles and soil-moisture can have considerable to do with the thickness of the film of capillary moisture. I believe if we had such a concept of the relation between soil-minerals and their behavior to water we could give much more satisfactory explanations of various moisture-relations in soils.

You will notice in Baver's discussion that he mentions the factors which Slichter used in measuring the movement of water and really had in mind the attraction between the soil-particle and water. I do not think you will find this given in any published literature. I gained this impression from talking to him a number of years ago. If we do know this attraction we can have much more definite factors to use in the formula proposed by Slichter.

F. J. VEIHMEYER (University of California)--The problem of the supply and movement of gases in the soil is in a less satisfactory state than is our knowledge of the supply and movement of water. The physical processes involved in this problem have not been given adequate attention by soil-physicists and plant-physiologists. L. M. Hutchins and B. E. Livingston have pointed out this deficiency.

The effect of tillage on aeration, perhaps, has been overemphasized in Baver's paper. Under the deep soil-conditions usual in the irrigated regions of the West, tillage probably has little effect upon aeration. While it may affect aeration in the shallow surface-layer which can be tilled, this is such a small portion of the total depth of soil occupied by the roots of most of the crops grown under irrigation, the effect may be discounted. Furthermore, limiting cultivation almost wholly to the destruction of weeds, as is being done with notable successes in many parts of California, is evidence that tillage is not essential for crop-production and, therefore, for aeration. Indeed there is a large amount of evidence that lack of aeration for successful crop-production is a rarity. Experimental work of W. A. Cannon which indicates that there is an exchange of carbon dioxide and oxygen between plant and soil may be cited in this connection. In connection with studies on the water-relations of fruit-trees, the writer, together with A. H. Hendrickson, has for several years irrigated trees so frequently, water has stood on the surface of the soil during most of the growing season, and yet no harmful results have been noted.

The trapping of air within the soil is frequently mentioned as an objectionable feature where flooding methods of irrigation are employed. Observation over a number of years with experimental plots and in commercial orchards, wherein a large portion of the land is submerged to considerable depth during irrigation, apparently has not interfered with infiltration of the water. I believe that air-trapping has little effect upon infiltration.

Diffusion is a very slow process and must be distinguished from the mass-flow of gases under differential pressure which is probably much more important than diffusion under field-conditions in causing exchanges of gases in the soil. Since adequate data is lacking, we can only guess as to the relative importance of these two phenomena.

Baver makes the statement that "diffusion-processes apparently account for most of the normal aeration of soils -----". This statement may need modification in view of the facts mentioned above as well as the important factor of displacement of air by water when the soil is wetted and the consequent movement of air into the soil when the water is used up. This latter effect is especially important in irrigated regions. The extreme slowness of diffusion of water-vapor through soils has been pointed out by a number of investigators. The diffusion of gases through soils may be of the same order of magnitude of slowness.

While in no way intending to discourage attempts, such as made in the paper, to analyze the basic conditions which determine soil-permeability to gases and water, attention is called to the conclusion reached by Slater and Byers [C. S. Slater and H. G. Byers, A laboratory study of the field percolation rates of soils, U. S. Dept. Agric. Tech. Bull. 232, 1931] from a study of the field-percolation rates of soils. "The field-percolation rate of a soil is governed more by the water passageways it contains (root-channels or structural cleavage) than it is by the character or volume of the pore-space of the soil-mass."

L. C. WHEETING (Washington State College)--In connection with the subject of soil-porosity and water-movements, it may be pointed out that permeability of a soil to water as measured by the rate of water-movement through it, is not a fixed property in individual fine-textured soils, and there is need for standardization of experimental conditions before significant permeability-values can be reported. Percolation-rates in most of the finer-textured soils of non-lateritic character, tend to decrease as time of percolation increases. A soil which allows 25 cc of water to percolate through it in one hour today may allow only 15 cc per hour to pass through tomorrow. It is suggested that this is a result of hydration and swelling of colloids. Their increased dispersion which results, causes a gradual clogging of the smaller spaces and brings about a decrease in continuity of water-conducting pores. Thus, permeability of a soil to water is dependent on the nature of its moisture-environment, just previous to making a test, and this situation makes it almost impossible to give quantitative expression to this property.

In considering soil-porosity and air-movement, it is worth recalling that Bouyoucos showed that the diurnal change in soil-temperature for the upper six inches amounts to as much as 12°F in certain sandy soils in Michigan. According to Charles' Law, the volume of a gas increases directly with an increase in temperature. Therefore, there must be a strong expulsion of air from the soil while it is warming up, and an equally significant intake of new air during cooling. Bouyoucos determined that one-half cubic foot of soil gives up 300-500 cc of air during a rise in temperature of 10°F. Since this exceeds that expected according to the law of Charles, it appears that the soil is not entirely passive in bringing about a change in soil-air. The volume of soil-air so affected, is undoubtedly greater than that exchanged daily through diffusion-processes. Probably the most complete change in soil-air is effected by the water from a heavy rain, as it penetrates into the soil and at least temporarily fills the pore-spaces. Subsequent intake of new air, as the soil slowly dries out, must be of some significance to plants.

Even changes of barometric pressure bring about an exchange of soil-air, according to the studies of Bouyoucos. He found atmospheric-pressure changes took place to depths of ten feet in a fine-textured soil. In the light of these investigations, it appears unlikely that diffusion-processes are the single "major cause of air-exchange between soil and atmosphere."

N. E. EDLEFSEN (University of California)--Previous reports of the Committee on Physics of Soil-Moisture have all dealt with some aspects of the topic discussed in the present report. Reference is made particularly to the 1934-35, 1935-36, 1936-37, and 1937-38 reports. By further concentrating the efforts of the Committee on this topic, it was felt that more progress could be made than if the efforts were devoted to another aspect of the physics of soil-moisture. This report might, therefore, be considered as a continuation along the same line as that previously followed by the Committee.

The equation for capillary flow of water through soils as given by Baver holds only, as pointed out by Richards and Bodman, for the restricted case of horizontal flow of a pure liquid of uniform concentration. Richards refers to Darcy's original statement in which it is clear that a more generalized statement of the flow includes consideration of the gravitational field, that is, it includes the force due to the gradient of the gravitational potential. It is customary in engineering literature to combine the pressure and gravitational potential in terms of what is called hydraulic head. This generalizes the equation so that it applies to flow of pure fluids in any direction. Anderson, however, points out that even the generalization to include the effect of gravity is not adequate to deal with problems of soil-moisture and especially to deal with the intake of soil-moisture by plants where the variation in concentration of dissolved material is an important factor. He refers to unpublished work of Edlefsen and Anderson in which the free-energy function is used as a basis for dealing with the dynamics of soil-moisture as well as its use by plants.

Givan refers to problems of flow where Reynolds' number is high in which case Darcy's equation is not applicable. This condition seldom exists in soils. It might, however, occur when steep pressure-gradients are applied to small samples of soil placed in tubes. It probably becomes important under certain conditions in some problems related to the flow of water into wells and drains as well as through rock-fill dams and filter-beds.

Richards proposes the name "dar," in honor of Darcy, for the unit of permeability of porous media appearing in his formal statement of Darcy's law. Wyckoff, Botset, Muskat, and Reed [see 1 of "References" at end of report] and Nutting [2] introduced the name "darcy" for the unit of permeability appearing in their equations for the flow through porous media. The permeability-coefficient referred to by Baver, Richards, Anderson (in above comments), and Wyckoff, Botset, Muskat and Reed, and by Muskat [3] have, in general, different dimensions and meanings. In some studies, it is probably preferable to use one form of the permeability-coefficient, while in

other studies, it might be more convenient to use a different form. It is customary in mathematical analysis to try to make any coefficients as universal as possible. In other words, to attempt to eliminate all variables. It is clear from the form of equation as used by either Baver, Richards, or Anderson (in above comments) or by Gilboy [4] or Buchanan [5] that the value of the coefficient is not independent of temperature since this variable affects the viscosity-term of the fluid. On the other hand, in the form of the equation as used by Fancher, Lewis, and Barnes [6], the viscosity-term is not included in the permeability-factor and hence these authors are able to present tables of the permeability of porous material having different degrees of porosity without saying anything about the temperature. In other words, the permeabilities as expressed by them are independent of temperature in so far as it affects viscosity, and depends only on the number, shape, and size-distribution of openings in the material. It might be supposed that the permeability would depend on the kind of fluid used to measure it. As shown by Fancher, Lewis, and Barnes, however, this is only true where the fluid apparently changes the structure of the material. In soils, having a considerable portion of colloidal material, of course, this condition exists whereas in most sands, it does not, and they get very good agreement between their coefficients of permeability of sands when measured by air and by water.

In view of these facts, the desirability of introducing a new name for a coefficient of permeability might be questioned. Also, if we want to name a unit of permeability, is it not just as desirable to name a unit of free energy, potential, or flow in analogy to what we have in electrical equations?

It is a common experience that, in general, the rate of entry of water into sandy soils is greater than in some loam-soils, and one often encounters the expression that the permeability of clay-soils is low as compared with sands. This latter statement is not always true. The rate of entry of water into some clay-soils is very high when first applied. This is especially true in a heavy clay-soil having a high colloidal content. When such a field has been dried out by a crop it will take water very rapidly when first applied until all the large openings are filled, and before the colloidal material has had time to swell. After this, the rate is greatly reduced and in general will be found to be less than in sandy soils. By the time the cracks are filled with irrigation-water, however, such fields usually contain as much water as it is desirable to apply.

Baver and a number of those commenting on his paper use the term "pF" which has come into fairly common use in the literature of soils. It is probably not out of place to raise the question as to the usefulness of this term. It will be noted that it is not a suitable function to use in discussing the dynamics of soil-moisture. In fact, it appears that the only justification for its use is that its value, as a function of moisture-content, can be graphed conveniently. This, it would appear, is hardly sufficient justification for its use. Since logarithms of either the potential-function referred to by Baver, Bodman, and Richards or the specific free-energy function referred to by Anderson are equivalent to the pF-term so that it is just as convenient, in making a graph, to plot the potential-function or preferably the free energy to a logarithmic scale. We could thus eliminate a superfluous term.

Veihmeyer calls attention to the unsatisfactory state of our knowledge relative to the supply and movement of gases in soils. His experience leads him to conclude that tillage has practically no effect on aeration of soils. He further concludes that entrapped air is not an important item in influencing the rate of penetration of irrigation-water into soils; whereas Horton thinks that entrapped air comes in rather critically in connection with the infiltration of water into soils.

Veihmeyer calls attention to the very slow rate at which gases diffuse through soils and he, like Wheeting, seems to feel that Baver has overemphasized the importance of this method of gas-exchange in soils. In this connection, attention is called to the work of Romell [7] in which he says that Walter Schmidt's claim that the microvariations in barometric pressure are important in soil-aeration is refuted by a simple computation using data published by Buckingham and by Schmidt and Lehmann. Diffusion, Romell thinks, remains the main factor.

A large number of pertinent questions have been raised in the discussions which should serve to stimulate future research. Several of the discussions emphasize the importance of factors which influence the overall rate of penetration under field-conditions. Such factors as stratification, root-channels, fertilizers, and the macrostructure in general have been referred to as having important bearing on the problem, especially under field-conditions, and should not be overlooked in interpreting experimental results.

The Chairman takes this opportunity of expressing his indebtedness to members of the Committee as well as to all others who were kind enough to send in comments and discussions.

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COMMITTEE ON PHYSICAL LIMNOLOGY, 1939-40

T. C. Adams, Chairman

The members of this Committee are: Carl B. Brown, Soil Conservation Service, Washington, D. C.; C. S. Howard, United States Geological Survey, Washington, D. C.; Tom C. Mead, United States Bureau of Reclamation, Boulder City, Nevada; M. R. Miller, Agricultural Experiment Station, University of Nevada, Reno, Nevada; Dr. A. H. Wiebe, Tennessee Valley Authority, Norris, Tennessee; Professor Joseph Kittredge, Jr., University of California, Berkeley, California; Dr. Thomas C. Adams (Chairman), University of Utah, Salt Lake City, Utah.

Appointments to the Committee were made February 16, 1940. It was directed to handle non-biological problems of limnology. Although much work has been done along this line, work which has very substantial scientific as well as immediately applicable value, the field of physical limnology has not been generally recognized as a separate one. Therefore, the Committee has been obliged to give more than usual consideration to its field of activity, and in the month intervening since its organization, has conducted correspondence between members with this in view.

The Committee is aware of scientific work being done on density-currents in lakes and reservoirs, the physics of wave-motion, sedimentation, heat-transfer, evaporation, light-values, and such phenomena and items of interest connected with lakes. It is to these and similar matters the Committee is turning its attention. The Committee also recognizes the value of studies of specific lakes in which a number of factors are considered, including inflow, evaporation, and special features. The Committee considers its duties to be mainly those of stimulating scientific work within its field, aiding in the correlation of this and obtaining recognition for the important work of lake-study. It will attempt to list activities under way, suggest new ones, and perform the other usual functions of Research-Committees of the Section of Hydrology.

University of Utah,
Salt Lake City, Utah

COMMITTEE ON UNDERGROUND WATERS, 1939-40

David G. Thompson, Chairman

The Committee on Underground Waters for the new triennium is composed of the following: H. F. Blaney; E. B. Burwell; W. Gardner; C. S. Howard; F. H. Lahee; G. W. Musgrave; A. M. Piper; A. C. Swinnerton; L. K. Wenzel; D. G. Thompson (Chairman).

The outstanding event of the year for ground-water hydrologists was the meeting of the International Association of Scientific Hydrology, as a part of the International Union of Geodesy and Geophysics, at Washington, D. C., in September, 1939. One day was devoted to "questions" or topics of symposia of the Commission on Subterranean Water.

The program of the meeting lists reports from six countries on question 1, namely, "Circulation of water and of water-vapor, and condensation of water-vapor, between the surface of the ground and the zone of saturation." The general summary-report on this question was given by H. E. Middleton and W. E. Davis. Reports were listed from six countries for question 2, namely,

"Definitions of the various kinds of underground waters." The general report on this question was prepared by O. E. Meinzer. Reports were listed from eleven countries on the third question, namely, "Determination of the runoff and physical conditions of flow of underground water in natural or altered ground, the flow being natural or induced." The general report on the question was prepared and read by L. K. Wenzel. Reports were received from 18 countries on the special subject of "Subterranean-water conditions and utilization and research in the subject" in the respective countries; and a general report on the subject was prepared by Dr. Meinzer. At a joint meeting of the Associations of Geodesy, Meteorology, Physical Oceanography, and Scientific Hydrology, C. V. Theis read a paper entitled "Earth-tides expressed in fluctuations of water-levels in artesian wells in New Mexico." Altogether about 60 reports were presented by the Commission on Subterranean Water. These reports represented all the continents and 27 different countries or colonial territories (counting Australia as one). (The Secretary of the Section of Hydrology of the American Geophysical Union, K. H. Beij, has a supply of "preprint" copies of some of the papers; and he should be addressed for information as to their availability.)

The Commission on Subterranean Water approved the following questions for discussion at the International Assembly in 1942:

(1) Infiltration (soil-absorption), factors that determine the infiltration-part of precipitation, including the effect of plants, land-configuration, etc., and the magnitude of these influences.

(2) Fluctuations of water-levels and artesian pressures in wells, their measurement and interpretation.

(3) The thermal springs of the respective countries, their geology, the origin and chemical composition of their water, and the source of their heat (in collaboration with the Association of Volcanology).

In addition to the three stated questions to be discussed in 1942, the Commission voted to continue the study of the principal concepts involved in the science of subterranean water, their definitions and classification, and to endeavor to agree upon terms for international use. It was also agreed to call for additional concise reports on ground-water conditions in the different countries such as were presented at the meeting of 1939.

The reports at the September, 1939, meeting on question 2, "Definitions of the various kinds of underground waters," were especially helpful. In June, 1939, Dr. Meinzer sent to representatives of the foreign countries adhering to the International Union a memorandum discussing the usage of terms in the different countries and suggesting for international adoption certain terms that seemed most useful. This memorandum is largely similar to his discussion printed on pages 674-677 of Part IV of the Transactions of the American Geophysical Union of 1939. One of his most significant suggestions was the introduction of the terms "phreatic water" and "piestic water" for waters that in the past have frequently been designated as "non-artesian" and "artesian" or "pressure" waters, respectively. He would subdivide piestic waters into hyperpiestic, mesopiestic, and hypopiestic waters, depending upon whether the water was under sufficient pressure to rise (a) above the land-surface, (b) above the zone of saturation but not above the land-surface, or (c) above the bottom of the confining bed, but not above the zone of saturation. Because of the small attendance at the September meeting, arising from the unsettled international conditions, no formal action was taken in regard to the international adoption of any terms.

In connection with this discussion of definitions of different kinds of subterranean water it may be noted that the Water Resources Committee of the National Resources Planning Board has distributed to a selected group for study a revised preliminary draft of a report on "hydrologic, hydraulic, and sanitary engineering nomenclature." This report has been prepared by a Committee composed of members of the American Society of Civil Engineers, the American Public Health Association, and the American Water Works Association. A cursory examination of this report shows that some of the definitions of ground-water terms should be modified and some terms should be added. It is hoped that during the year members of the Committee on Underground Waters may be able to review the definitions in regard to ground-water hydrology and make suggestions in regard to them. There has been considerable evidence in the last two or three years that there is need of clarifying or restricting the meaning of certain ground-water terms and finding new terms to describe concepts that have recently been developed.

Mention may also be made of the report recently published by the National Resources Planning Board on "Deficiencies in hydrologic research." This report outlines, under nine items, some of the problems of ground-water hydrology that deserve especial study. During the time that has elapsed since this report was undertaken and the first draft of parts of it were prepared, considerable progress has been made in getting information on some of the problems discussed, for example, in regard to field-methods of determining the permeability of water-bearing formations.

Because of the expense involved in drilling of wells needed for the study of some of the problems described, the accomplishment of the objectives generally must necessarily await favorable opportunity for making observations in connection with developments of new supplies of ground-water. However, it is noteworthy that more and more of those most directly concerned with practical problems realize the value of experimental work. For example, during the past year some 14 or more test-holes were drilled by the City of Houston Water Department, some of them to depths of 2,000 feet or more, solely for informational purposes, and pumping tests to determine the permeability of the water-bearing sands were made on five wells.

The number of areas, as well as the number of wells, in which observations are made of fluctuation of ground-water level continues to expand. The annual report of the Federal Geological Survey for 1939, now in press, will contain records of measurements of about 5,500 wells in 35 States and the Territory of Hawaii. This is about 500 wells and three States more than were reported in the report of 1938, which was published late in 1939 as Water-Supply Paper 845. Other agencies have continued to measure a large number of wells, notably the Soil Conservation Service, the Forest Service, and several agencies in California.

Some facts shown by the 1939 Geological Survey report on ground-water levels may be stated briefly. In 1939 the total precipitation for the year was below normal in most of the States along the eastern seaboard, and in all States west of the Mississippi River except Arkansas. As a result the water-levels in many localities at the end of 1939 were generally lower than at the end of 1938. In several of the States in the eastern part of the country the precipitation was above normal in the first part of the year and in some places the ground-water reached the highest level during the period of record. Subsequently, in the late part of the year precipitation was considerably below normal and the water-level dropped rapidly, in some places to record low levels. In the central and western States in many wells the water reached the lowest level during the period of record. However, in most of the areas under observation the record does not extend back more than five or ten years.

Among unusual fluctuations of water-level revealed in the program of water-level measurements, brief mention was made in last year's annual report of observations in Utah and elsewhere, showing fluctuations caused by distant earthquakes. These observations have recently been published in a paper by H. E. Thomas, of the Federal Geological Survey [see reference 1 at end of this report]. Of 42 observation-wells in California, Utah, and New Mexico that are equipped with automatic water-level recorders, 30 wells showed a fluctuation during an earthquake that occurred on November 10 with its epicenter at latitude 56° north, longitude 159° west, near the coast of the Alaskan Peninsula. The water in the wells rose above and fell below the level at which it stood just before the disturbance, but eventually returned to a level that appeared to continue the trend established just before the shock occurred. The maximum observed fluctuation, observed in a well near Tooele, Utah, was 0.87 foot; and the seismic fluctuations continued for nearly three hours. In three other wells the fluctuation exceeded 0.4 foot. During the destructive Chilean earthquake of January 24-25, 1939, with epicenter at latitude 37° south, longitude 73° west, slight fluctuations were recorded in one well in New Mexico, one well in southern California, and five wells in Utah. The maximum fluctuation was only 0.03 foot, and the most noteworthy feature was the great distance from the observation-wells to the epicenter of the earthquake. Although instrumental records of fluctuations of water-level caused by earthquakes have been reported by several persons, in most of the instances the distance between the epicenters and the observation-wells has not exceeded 500 miles.

As this report is about to be submitted for publication, C. V. Theis has reported a fluctuation of 0.7 foot in a recorder at Hot Springs, New Mexico, at the time of an earthquake in the Imperial Valley, California, on the night of May 18-19, 1940. W. P. Cross reports that on the same date there were noticeable and unusual fluctuations with a maximum of 0.90 foot, in 10 out of 16 wells equipped with automatic water-stage recorders in the vicinity of Miami, Florida. Theis also reports a fluctuation of 0.40 foot in the well at Hot Springs, New Mexico, which is believed to have coincided with a recent destructive earthquake in Turkey. Following these reports other members of the Division of Ground Water of the Federal Geological Survey have been asked to study charts from automatic water-level recorders in their territory. Already, M. A. Warren has found a fluctuation of 0.14 foot in a well that occurred about an hour after the reported time of the Turkish earthquake, which was December 26, 1939, at $23^h\ 57^m$ GMT; and a fluctuation of about 0.22 foot that occurred within a very short time after the California earthquake which occurred at $04^h\ 36^m$ GMT, May 19. R. R. Bennett reports a fluctuation of about 0.07 foot in a well near Brackettville, Texas, that apparently resulted from the Turkish earthquake. A. N. Sayre reports that the California earthquake produced fluctuations in three wells in the Pecos Valley, in Texas. The maximum fluctuation was about 0.7 foot. C. L. McGuinness reports that a recorder operated on a well in Indianapolis, Indiana, showed a small fluctuation at the time of the Turkish earthquake. This well also appears to show earth-tides. It seems likely that

fluctuations due to these earthquakes will be found on other recorders. Although some of the difference in amount of fluctuation in different wells may be attributed to differences in the sensitivity of the recorders, there remain for consideration interesting questions of whether the amount of fluctuation recorded may be different in different types of material, different diameters, and different depths of wells, etc.

Reference has been made in several past reports to the sinking of land in Santa Clara Valley, California, which is believed to have been the result of compression of water-bearing formations as they have been dewatered; but there has been presented no ground-water data to definitely support this belief. At the South Pacific Regional Meeting of the Section of Hydrology, in January, 1940, Professor C. F. Tolman and J. F. Poland described some of the relations between withdrawal of ground-water and subsidence of the land in Santa Clara Valley. Their paper on "Ground-water, salt-water infiltration, and ground-surface recession in Santa Clara Valley, Santa Clara County, California" is published in the Transactions of 1940 [Part I, pp. 23-34]. They report that releveling has shown that subsidence has occurred in an area of about 200 square miles, and the maximum amount of subsidence has been 5.5 feet. It is noteworthy that the subsidence has occurred only where the water-bearing horizon is overlain by clay; and Tolman attributes the subsidence to the fact that water was squeezed from the clay as the artesian pressure on the water in the aquifer was reduced. There was practically no subsidence from 1937 to 1939, and during that period the ground-water head rose about 50 feet [2]. This raises a question as to whether, with possible further increase in the artesian head, the process of movement of water from the clay will be reversed so that it will move into the clay, cause it to swell and the land to rise to its original level, or whether, as the factor of time is extended the process becomes essentially irreversible as demonstrated for certain soils by Terzaghi [3].

Recent changes of elevations of the land-surface in the vicinity of Los Angeles have been described by U. S. Grant and W. E. Sheppard [4]. In some parts of the region there has been subsidence, but in other parts the land has risen. The authors discuss, as possible causes of the changes in elevation, tectonic movements, removal of oil in oil-fields, and changes in the ground-water level.

Also of interest as bearing on the problem of compressibility and elasticity of formations is a paper read by Professor W. P. Kimball at the New York meeting of the American Society of Civil Engineers in January, 1940, which showed that the foundations of the Huey P. Long Bridge near New Orleans rise as the stage of the Mississippi declines, and fall as the stage of the River rises [5]. The change in level of the piers is reported to be of the magnitude of one two-hundredth of a foot for each foot change in stage of the River.

Problems relating to the contamination of fresh ground-water by salt water are demanding an increasing amount of attention in several parts of the country. Mention has been made in past years of investigations of salt-water problems in areas on Long Island, New York, the coast of New Jersey, the Sarasota area, Florida, the Galveston-Houston and El Paso areas in Texas, and the Pecos Valley in New Mexico. Some of the results of an investigation that has been in progress for several years in the Parlin, New Jersey, area are described in a paper by H. C. Barksdale which is published in these Transactions. During the past year new ground-water investigations that include study of the salt-water problem have been undertaken by the Federal Geological Survey in the Miami and Pensacola areas, in Florida, in the Texas part of the Pecos Valley, and in the coastal plain area that extends southward from Los Angeles. In the Southern California area there is not merely the problem of the possible danger of contamination by water from the ocean, but also the question of whether there may be any contamination by salt water from the many oil-wells that have been drilled in the region.

Among problems under investigation by the Federal Geological Survey in cooperation with the States and other Governmental agencies, S. F. Turner reports that an inventory is being made of the water-supply of two separate parts of the Upper Gila River Valley, in the vicinity of Duncan and Safford. Also studies are being made of the use of water by salt-cedars and cottonwood-trees on the bottom-land of the Gila River in these areas.

R. M. Leggette reporting investigations by the Federal Geological Survey in cooperation with the New York Water Power and Control Commission and Nassau and Suffolk counties, states that the studies by M. L. Brashears, of salt-water contamination in Kings and Queens counties, Long Island, New York, show the chloride-content is still increasing in certain areas as a result of overdraft. Other studies show that in certain areas the temperature of the ground-water is increasing slowly as a result of returning to the ground warm water used for air-conditioning. Extensive pumping tests have been made on Rockaway Beach to determine the permeability of the Lloyd sand. During April, 1939, ground-water levels on Long Island east of Kings County, were at the highest level since about 1903, and some were higher than in that year. However, because the precipitation in

the last part of the year was small the high stages were not maintained and at the end of 1939 the water-level in many wells were lower than at the corresponding times in 1938.

H. C. Barksdale, reporting on investigations by the Federal Survey in cooperation with the New Jersey Policy Commission, states that, beginning in May, 1939, the water-level in a key observation-well was lower during many days than on corresponding days in previous years since observations began in 1923. He also reports that in Atlantic City the chloride-content in samples of water from a considerable number of wells was slightly higher than at any other time since the period of records, which for some wells began in 1923.

John C. Frye reports, in regard to the effects of withdrawal of water in the Meade Artesian Basin, in southwestern Kansas, shown by an investigation by the Federal Geological Survey in cooperation with the Kansas Geological Survey and the Kansas State Board of Health: "The first flowing well was drilled in this Basin in 1886, and since that time approximately 1,000 wells have been drilled, of which only a few hundred are now in usable condition. W. D. Johnson in 1899 reported that the maximum head was 22 feet above land-surface, and estimated the total flow from wells at 1,800 gallons a minute. Forty years later, in 1939, the maximum heads were between 17 and 18 feet above land-surface, and the total flow, estimated from about 200 flow-measurements, representing about four-fifths of the usable wells in the area, was 2,500 to 3,000 gallons a minute. During the last 40 years the head appears to have declined but slightly, and the total flow has been increased substantially. This appears to be explained by the decreased flow during this period from artesian springs in the area, for whereas the present total spring-discharge is estimated at 3,000 gallons a minute, it is known to have been considerably greater in the past."

H. F. Blaney reports on work by the Division of Irrigation of the Soil Conservation Service as follows: "In connection with the Division of Irrigation's consumptive use of water-studies in the Pecos River (New Mexico-Texas) Joint Investigation, it has been necessary to establish observation-wells in three sections of the drainage-basin in cooperation with the Ground Water Division of the Geological Survey. Inflow-outflow consumptive-use areas have been set up at Ft. Sumner, New Mexico, Carlsbad, New Mexico, and Imperial-Zimmerman, Texas; and another is being established at Ft. Stockton, Texas. Depth to ground-water measurements are being taken several times during 1940 as a means of estimating the change in ground-water storage in the inflow-outflow areas.

"In addition to the above our Division has established an Evapo-Transpiration Station at Carlsbad, New Mexico, for the purpose of determining the use of ground-water by native vegetation such as salt-grass, sacaton, salt-cedar, and tules by means of lysimeters. I understand that results of this study may be used in estimating ground-water supplies in some areas along the Pecos River."

Dr. Willard Gardner reports as follows on the work of himself and colleagues at the Utah State Agricultural College and Agricultural Experiment Station:

"Dr. Kirkham has continued his studies regarding the spacing of tile-drains over an artesian basin. A follow-up paper discussing the theory of the problem presented in last year's Transactions is published in the Transactions of 1940 under the title 'Artificial drainage of land: Stream-line experiments, the artesian basin--II.' He is at the present time conducting model-tests to check his theory of the flow of water into tile-drains over hardpan. (An abstract of the theory was published on the program of the meeting of the American Physical Society held in Washington, D. C., in May, 1940.) One interesting prediction of the theory is that more water will flow into drains if they are placed a certain distance above the hardpan rather than next to it.

"Dr. Israelsen and I have completed a short paper on the design of drainage-wells and are presenting it for publication in an engineering journal. It has been a matter of considerable interest to us and possibly it may be of some interest to others.

"We have in Cache Valley and in other parts of Utah much land that is water-logged because of artesian pressure. In previous papers we have indicated some of the difficulties arising in attempts to make use of drain-tile. We have discussed also the problem of determining the effective diameter of a network of wells and have proposed using drainage-wells in place of tile with the view of developing irrigation-water and at the same time draining the overlying water-logged land.

"In the paper we have just completed we consider a network of wells all of the same diameter arrayed in concentric circles and connected to a central well by means of horizontal pipes lying near the surface of the ground. We assume that the cost of pipe is proportional to the product of the length and diameter, take account of the friction-head in the pipes and in the water-bearing material, and express the total cost in terms of the various parameters of the network and so determine these parameters as to make the cost a minimum.

"The numerical results obtained depend of course on various local costs and would perhaps

be of no special interest here. Suffice it to say, however, the problem seems to be resolved by this procedure."

Dr. F. H. Lahee has submitted the following statement in regard to studies of ground-water in connection with problems of the production of petroleum:

"There is nothing of an exceptional character to report on problems of underground waters associated with oil. Data are being systematically accumulated on the 'connate water' present in oil-bearing sands, but a complete understanding will not be possible until the technique of taking bottom-hole cores under pressure has been improved.

"The study of disposal of oil-field waters, that is, of water brought up with the oil, is receiving much attention by engineers. Some success has been had in pumping these waters back into the oil-sands, down dip from the lower edge of the oil-pool, but difficulty is often experienced due to precipitation of salts which soon choke the pores and so retard or prevent further ingress of the water. Various chemical solvents have been tried, with varying results. This procedure should be of considerable interest to students of the physical conditions attending the occurrence and movements of underground waters. The subject is discussed by A. S. Rhea and E. B. Miller in an article entitled 'Disposal of salt water in the east Texas field' [Tech. Paper 1151, Amer. Inst. Min. Eng., February, 1940]."

Edward B. Burwell, Jr., reports as follows on some activities of the United States Corps of Engineers:

"In connection with investigations for local flood-protection works in the Cincinnati (Ohio) and Lawrenceburg (Indiana) areas the Cincinnati District office has established a number of ground-water observation-wells and measurements are being taken twice daily.

"In the lower end of the Mill Creek Valley, along the proposed barrier-dam site, three holes drilled to bed-rock and cased to within a few feet of the bed-rock surface have been measured twice daily since September, 1939. Graphs showing daily elevations of the piezometric surface and the Ohio River surface are being kept up to date.

"At Lawrenceburg, two lines of wells of six each, one normal to the Ohio River and extending for a distance of 6,000 feet back from the River and the other parallel to the River 2,300 feet from it, have been measured twice daily since December 6, 1939. These wells extend below the flood-plain silt-blanket to a minimum depth into the underlying sand and gravel of ten feet and are cased with perforated pipe below the blanket. Graphs showing the ground-water and river-surface elevations daily are being kept up to date."

Mr. Burwell has also prepared a statement in regard to the possibility of determining the position of the water-table by the seismic method, which is published as Appendix A of this report.

A report by Professor A. C. Swinnerton on "Research on hydrology and physiography of limestone terranes" is published as Appendix B.

The Hydraulic Laboratory Bulletin, No. VIII, for January, 1940, published by the National Bureau of Standards, lists several projects as follows, which may be of interest to ground-water hydrologists.

Two cooperative projects at the University of Iowa involving the Iowa Institute of Hydraulic Research and the United States Geological Survey, and, on one project the United States Department of Agriculture, in connection with the measurement of rainfall and runoff, also include observations on fluctuations of ground-water in two drainage-basins, namely, Ralston Creek and Rapid Creek.

At the University of Illinois a project under the direction of Professor H. E. Babbitt has for its purpose the testing of existing hypotheses of the flow of water into wells.

The Colorado Experiment Station, in cooperation with the Soil Conservation Service, under the direction of W. E. Cole, has in progress a project to determine the extent to which ground-water is used for irrigation in an area along the South Platte River and its possible affect upon the return flow of the River. The same organization is measuring about 110 observation-wells in the valleys of the South Platte and Arkansas Rivers.

In connection with studies to determine the effect of filling its reservoirs on the adjacent water-table, the Hydrography Section of the Tennessee Valley Authority, under the direction of G. N. Burrell, is comparing fluctuations of water-level in observation-wells with rainfall and river-stages.

References

[1] H. E. Thomas, Fluctuations of ground-water levels during the earthquakes of November 10, 1938, and January 24, 1939, Bull. Seis. Soc. Amer., v. 30, pp. 93-97, 1940.
[2] A brief note in Engineering News-Record, June 22, 1939, p. 56, states that the land has risen slightly; but the rise is apparently not commensurate with rise in ground-water head as compared to corresponding changes when the head was dropping.
[3] Charles Terzaghi, Principals of final soil classification, Mass. Inst. Tech., Pub. 63, pp. 41-43, 1927.
[4] U. S. Grant and W. E. Sheppard, Some recent changes of elevation in the Los Angeles basin of southern California, and their possible significance, Bull. Seis. Soc. Amer., v. 29, pp. 299-326, 1939.
[5] W. P. Kimbal, Settlement studies of Huey P. Long Bridge, Civ. Eng., pp. 145-148, March, 1940; also abstract, Eng. News-Record, v. 135, p. 25, 1940.

U. S. Geological Survey,
Washington, D. C.

APPENDIX A--DETERMINATION OF GROUND-WATER LEVELS BY THE SEISMIC METHOD

Edward B. Burwell, Jr.

For the past one and one-half years the Corps of Engineers, United States Army, has made use of the refraction-seismic method on preliminary foundation-investigations for proposed dams in various parts of the Ohio River Basin and elsewhere. The primary object in making these investigations has been to determine approximate elevations of the bed-rock surface at several possible sites for a proposed structure in order to select the site at which the configuration of the bed-rock surface appeared to be most favorable for foundation-purposes and to confine drilling operations to the favorable site.

Incidental to the studies of the seismic records for the primary purpose stated above, it has been noted that a number of the records indicate the possibility of determining the elevation of the water-table within rather small limits of error.

Without going into the details of the methods involved in refraction-seismic explorations, the general principles which permit the segregation of bed-rock from overburden and of the zone of saturation in overburden from the unsaturated overburden may be described briefly as follows: When a seismic wave is set up in any material, it will be transmitted through the material at a velocity which depends upon the ratio of the elasticity to density of the material; the higher the value of this ratio the greater is the velocity of the seismic wave. The value of the ratio of elasticity to density (and consequently of the velocity of seismic-wave transmission) appears to be least for a dry unconsolidated material, such as a dry sand, and to be greatest for a highly consolidated material, such as an unaltered granite. There are all gradations of values between these extreme limits, bearing in mind that reference is here made only to materials in the outer crust of the Earth. Once the velocities of seismic-wave transmission have been obtained for each stratum in a vertical series from the ground-surface down to bed-rock, the thickness of each stratum can be computed.

Investigations to date show conclusively that there is sufficient difference between the velocity of seismic-wave transmission in overburden and in bed-rock to distinguish between those two types of material. The investigations have given strong indications that the velocities are sufficiently different in unsaturated overburden and in saturated overburden to distinguish between these types of material also. This latter statement is especially true as applied to investigations which have been carried on in river-valleys which are deeply filled with alluvium. Everywhere under such conditions a velocity of wave-transmission has been obtained which appears to be characteristic of the saturated portion of the alluvium and which is markedly higher than velocities obtained in the overlying unsaturated alluvium. The fact that this difference in velocities is due to the difference in water-content of the alluvium and not to changes in the character of the alluvium itself is borne out by comparisons with the results of core-borings which it has been possible to make in a number of instances. Moreover, these comparisons established a close agreement between the depths to the water-table as obtained by the seismic method and as actually measured in the borings.

The velocity which is characteristic of the saturated overburden averages somewhat higher than the known velocity which characterizes water in the majority of cases. In fact, it appears

that the elasticity-density properties of the water in a saturated overburden affect the velocity obtained to such a degree that the nature of the overburden itself can vary widely without greatly affecting the magnitude of the velocity. That is, the evidence indicates that a saturated alluvium which is predominantly sand will give a velocity which differs but little from one obtained in a saturated alluvium which is predominantly silt or clay. There may be some exceptions to the foregoing general statement. There undoubtedly is an exception in the case of a saturated, compact glacial till, which has a characteristic velocity considerably higher than that obtained in any other type of overburden in the Ohio River Basin.

On the basis of the evidence that the velocity obtained in a saturated material appears to be influenced primarily by the properties of the water rather than by the properties of the material itself, it is concluded that the seismic method will not afford satisfactory differentiation between a good aquifer and a material which would yield relatively little water.

Although the evidence points to the possibility of obtaining the depths to the water-table under most conditions, there are some conditions under which it would be impossible to obtain such data by the seismic method. Most notably these latter conditions are those in which the water-table lies below the bed-rock surface, or at a small distance above the bed-rock surface as compared to the depth from the ground-surface to the water-table. Under such conditions only the seismic-wave velocities characteristic of the unsaturated overburden and of the bed-rock would be obtained and the velocity characteristic of the zone of saturation could not be detected.

Corps of Engineers, U. S. Army,
Cincinnati, Ohio

APPENDIX B--RESEARCH ON HYDROLOGY AND PHYSIOGRAPHY OF LIMESTONE-TERRANES

A. C. Swinnerton

Current research in the hydrology and physiography of limestone-terranes is reported from distinctly varied fields and the number of investigations and the extent of interest seem to be expanding. The information available for this report ranges from theory to fact, and from the origin of caves and the relation between meteorite craters and sink-holes to the additional evidence which is accumulating about deep-seated solution-cavities.

In the study of the origin of limestone-caverns, J. Harlen Bretz has extended his examinations of caves in the eastern, mid-western, and southwestern United States to include a large number of caverns which show significant relations to local structure and physiography. In addition Professor Bretz is giving special attention to the type of cavern, usually filled, which immediately underlies unconformities.

Recently there appeared a publication by Edward L. Tullis and John Paul Gries on the Black Hills Caves [Black Hills Engineer, v. 24, pp. 233-271, 1938]. An investigation of these caverns has been long overdue and the present contribution is an excellent study of the unique characteristics of crystal lining, network veining, drip-stone and cavern form, and filling of caves involved in a regional history of more than one erosional cycle. The authors attempt to relate the various types and stages of cavern-development to the rather sketchily known physiographic history of the Black Hills. They conclude that an early, deep-seated, structurally controlled, artesian circulation was developed in the Pahasapa limestone in early Tertiary time. Structural uplift near the end of the Oligocene was responsible for a change in climatic conditions which the authors tentatively conclude caused the change from solution to crystal-deposition within the caverns which were still below the water-table. Solution was renewed by early Quaternary time by circulation just below the water-table, followed by Quaternary uplift and drainage of the caves.

In the interior region of Carboniferous limestones, Clyde A. Malott has extended his studies of karst physiography to a study of the development of karst valleys in both southern Indiana and Kentucky. In a paper presented at the Columbus meetings of the American Association for the Advancement of Science [Karst valleys, abstract, Geol. Soc. Amer. Bull., v. 50, p. 1984, 1939] he outlined the development of karst valleys where normal surface-drainage has been superposed from overlying clastic formations onto underlying limestones. He pointed out that early stages still clearly show the dendritic arrangement of the former surface-streams, but only traces of the earlier surface-stream patterns are shown in the later stages. The present underground drainages of these terranes are directed from beneath the karst valleys into the deeper surface-streams, frequently many miles from the sinking streams. Professor Malott suggested that the present diversions of the vadose waters from the karst valleys, ending in the distant karst springs, have a distinct bearing on the manner of cavern-development.

E. R. Pohl has completed the geologic map of the Mammoth Cave special sheet which is now in the hands of the National Park Service. He is continuing his field-work looking toward the completion of the geologic mapping of the Horse Cave, Mumfordville, Mammoth Cave and Cub Run quadrangles. His report of the geology of the Mammoth Cave National Park is nearing completion.

In Alabama, Walter B. Jones, now Director of the Department of Conservation of Alabama, on leave of absence from the State Geological Survey, writes: "For a number of years I have been doing some work in caves. I have been making sketches of the caves and caverns; estimating the flow of water at various seasons of the year and in various parts of the caves; collecting cave faunas which are giving some indication of the extent of the caverns and their relationships one to another; and gaining such other information as I could get. We still have a number of caves here in Alabama which are as yet unexplored by us .....

"I do not have very much time to give to this work and it will be several years before I can complete my studies. Some day we will publish a report on Alabama caverns and that report will seek to show movements of ground water, faunas, etc."

In the work of the Tennessee Valley Authority the history of past limestone-solution has continued to be a factor influencing engineering practice. Edwin C. Eckel writes: "The dams which show the greatest points of interest for underground solution are those of Chickamauga, Coulter Shoals, and the two which were taken over from the Tennessee Power Company, Great Falls and Hales Bar. All of these are contributing toward our knowledge of what really happens below the surface of limestone-rocks, and I think we are gradually getting around to something like a formal statement on the subject so far as southeastern climatic conditions are concerned."

B. C. Moneymaker has published two brief abstracts bearing on the deep solution of limestones in the Tennessee Valley Authority region. The titles of these abstracts are: Deep solution cavities in the Tennessee Valley Area, Geol. Soc. Amer. Proc. 1937, p. 101, 1938; Origin of deep pools in the channel of Tennessee River, Geol. Soc. Amer. Bull., v. 50, pp. 1923-1924, 1939.

Moneymaker is continuing his study of deep sub-river cavities and expects to have a publication on the study within the next year, and R. F. Rhoades has prepared for publication a report on the engineering geology of the Gilbertsville dam-site. Here the flood-plain of the lower Tennessee River is supplied with water under low artesian head from the adjoining highlands. A dual system of pressure-surfaces is established because of the differential in the transmission-capacities of the alluvial sediments of sand and gravel capped with clay, and the solution-channeled limestone which forms the bed-rock valley-bottom. At the River the piezometric surface created by artesian flow in the limestone is four feet above the free surface of the River; the pressure-surface determined by the flow through the alluvial filling coincides with the level of the River. The two pressure-surfaces coincide only at some distance from the River.

In addition to these individual studies the Tennessee Valley Authority is publishing a rather comprehensive report of the engineering geology of all of the principal dam-sites. It will be designated Bulletin 11, Geologic Division, Tennessee Valley Authority, and will carry a general introduction by Major Eckel, Chief Geologist. It is expected to be issued in March or April, 1940, under a December, 1939, date.

From Earl A. Trager, Chief, Naturalist Division, Branch of Research and Information of the National Park Service, comes the information that the Park Service received reports during the year on subjects relating to caverns as follows: A report on some guano deposits in Carlsbad Caverns National Park, by Ross A. Maxwell; A report on the development of Florida Caverns, by William M. McGill; A preliminary geologic report on the "New Discovery" in Mammoth Cave National Park, by D. C. Hazlett; Inspection of Crystal Cave, Sequoia National Park, by H. E. Rothrock.

The investigation on caves, reported here three years ago, by J. Volney Lewis of the National Park Service, is still unpublished. It includes a survey of cave-literature, reports of examinations of caves, the formation of cavern-features, and the origin of caves.

V. T. Stringfield writes: "I have noted with a great deal of interest the record of a well, drilled last year, 10,000 feet deep in south Florida which contains additional information indicating cavities at considerable depths. According to Robert B. Campbell 'three pronounced caverns' were penetrated at '2,846 to 2,864, 2,958 to 2,963, and 2,986 to 2,997 feet'" [Amer. Ass. Pet. Geol., v. 23, pp. 1713-1714, 1939].

"Last October the United States Geological Survey began an investigation of ground-water conditions in southeast Florida and in connection with that work I expect information of interest ..... will be obtained concerning the Pleistocene limestone (Miami Oolite)..... This limestone crops out in southern Florida, only a few feet above sea-level..... and contains numerous vertical

channels or natural wells ranging in diameter from a few inches to a foot or more filled with permeable unconsolidated quartz-sand. In some localities the horizontal distance between natural wells ranges only from a few inches to a foot or two. The wells extend to some depth below sea-level.

"A few observations after large rains indicate rapid percolation of water into the limestone with little or no surface-runoff. However, lateral movement of the water through the formation apparently is not so free, and it suggests to me that much of the vertical movement is through the natural wells filled with permeable sand.

"As has been indicated in Water-Supply Paper 773-C, percolation of water through sink-holes filled with sand in the Lake Region of Florida appears to constitute important recharge to the Ocala (Eocene) and Tampa (Miocene) limestones, the principal artesian formations in Florida. Some of these filled sinks apparently extend to a depth of 200 feet or more. Natural wells in these formations have also been noted. The cross-sections of a few of these wells exposed in quarries show that some of the wells terminate at a level or zone where there are cavities or channels indicating free lateral movement of ground-water. Records of wells suggest the presence of these permeable zones below the water-table and I believe that it will be possible to correlate them with the marine terraces after sufficient data have been obtained .... In the co-operative work with the Florida Geological Survey during the past year a field-test on a select group of artesian wells in northeast Florida was made to determine the permeability of the Ocala limestone (Eocene) in that area ....."

An interesting controversy has developed following the publication by H. M. Fridley of a paper on "Solution and stream piracy" [J. Geol., v. 47, pp. 178-188, 1939]. Professor Fridley's conclusion that the South Branch of the Potomac River had developed its course through the Smoke Hole, as a result of stream piracy brought about by relatively deep-seated solution of the Oriskany formation, was challenged by Karl Ver Steeg. In the American Journal of Science [v. 238, pp. 32-41, 1940] Professor Ver Steeg contended that the Smoke Hole is not abnormal if the hypothesis of superposition be assumed for Appalachian drainage and cited various items of physiographic evidence to support his contention. Professor Fridley replied [Amer. J. Sci., v. 238, pp. 226-233, 1940], submitting further evidence in favor of stream piracy by solution.

During the year the West Virginia Geological Survey issued Volume XII, "Limestone of West Virginia," by John B. McCue, John B. Lucke, and Herbert P. Woodward. Including a map of limestone-areas, over a thousand analyses of limestones, and topographic descriptions of outcrop-areas, it is a valuable reference-volume for West Virginia.

An instance of a small cave formed by the depositional work of spring-water was reported by A. C. Swinnerton at the Columbus meetings of the American Association for the Advancement of Science [Constructional "Cave" in Calcareous Tufa, abstract, Geol. Soc. Amer. Bull., v. 50, p. 1990, 1939].

In New Mexico the United States Geological Survey has shifted the emphasis of its studies from the observation of artesian conditions in the Roswell Basin where the important aquifer is limestone to the solution of the Permian salt and anhydrite in the lower Pecos Valley. A. M. Morgan, formerly at Roswell, is now carrying on this work under the direction of Charles V. Theis. The investigation is also being extended into the Texas part of the Pecos Valley under the direction of A. N. Sayre.

John D. Boone and Claude C. Albritton, Jr., presented a provocative paper at the Columbus meetings of the American Association for the Advancement of Science under the title "Possibility of an additional meteorite crater near Odessa, Texas." The paper has now been published [Field and Laboratory, v. 8, pp. 11-18, 1940]. In the vicinity of Odessa, Texas, is a well-known meteorite-crater. Near it are a number of sink-holes which closely resemble the crater in general configuration. Professors Boone and Albritton suggest that at least one of these sinks may be a meteorite-crater modified by the solvent action of ground-water on the underlying bed-rock. This interesting hypothesis brings to mind the controversy between the proponents of the meteoritic origin of the Carolina bays and the view taken by Professor Douglas Johnson that the Carolina bays represent thinly-veiled sink-holes in the Coastal Plain limestones underlying a shallow veneer of recent sediments. Professor Johnson's book on the origin of the Carolina bays is expected to appear during 1940.

During the last few years geologists have been much concerned with the problem of the submarine canyons. The existence of a few has been known for some years, but the extent of this rugged submarine topography is now well established by the charting of the continental slopes and the issuance by the Geological Society of America, of Special Papers No. 7, by Veatch and Smith. In several numbers of the Journal of Geomorphology [v. 1, No. 2, through v. 2, No. 3]

Professor Douglas Johnson reviewed the many theories suggested to explain the origin of submarine canyons. He advocates strongly the theory of their development by the sapping action of artesian springs. Since the regional geology demands that at least some of these springs are related to water-circulation and solution-work in limestone, the unique character of the hydrology of limestones may have significance in the discussion of this puzzling problem of submarine physiography.

Antioch College,
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COMMITTEE ON DYNAMICS OF STREAMS, 1939-40

Lorenz G. Straub, Chairman

The Committee on Dynamics of Streams has continued during the past year with almost the same membership as before. One new member has been added. The membership is now as follows: K. Hilding Beij, National Hydraulic Laboratory, U. S. Bureau of Standards, Washington, D. C.; H. H. Bennett, Director, U. S. Soil Conservation Service, Washington, D. C.; Irving B. Crosby, Consulting Geologist, 6 Beacon Street, Boston, Massachusetts; John B. Drisko, 34 West Baltimore Street, Kensington, Maryland; H. V. Gelb, Division of Research, U. S. Soil Conservation Service, College Station, Texas; C. S. Howard, Chemist, U. S. Geological Survey, Washington, D. C.; E. W. Lane, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa; W. C. Krumbein, Department of Geology, University of Chicago, Chicago, Illinois; L. M. Lawson, American Commissioner, International Boundary Commission, First National Bank Building, El Paso, Texas; W. C. Lowdermilk, U. S. Soil Conservation Service, Washington, D. C.; Gerard H. Matthes, Mississippi River Commission, Box 363, Vicksburg, Mississippi; G. W. Musgrave, U. S. Soil Conservation Service, Washington, D. C.; Martin E. Nelson, Engineer, U. S. Engineer Sub-Office, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa; M. P. O'Brien, College of Engineering, University of California, Berkeley, California; R. L. Parshall, Colorado State College, Fort Collins, Colorado; G. W. Pickels, Department of Civil Engineering, University of Illinois, Urbana, Illinois; C. H. Pierce, Senior Engineer, U. S. Geological Survey, Washington, D. C.; C. E. Ramser, Watershed and Hydrologic Studies, U. S. Soil Conservation Service, Washington, D. C.; William W. Rubey, U. S. Geological Survey, Washington, D. C.; Fred C. Scobey, U. S. Department of Agriculture, Room 219 P. O. Building, Berkeley, California; Lorenz G. Straub, Chairman, University of Minnesota, Minneapolis, Minnesota; Roy N. Towl, Consulting Engineer, 506 South Fifty-Seventh Street, Omaha, Nebraska; A. C. Trowbridge, Department of Geology, University of Iowa, Iowa City, Iowa; Herbert D. Vogel, Fort Belvoir, Virginia; H. H. Wheaton, Department of Mathematics, Fresno State College, Fresno, California; N. E. Winters, State Agricultural College, Stillwater, Oklahoma.

At last year's meeting of the American Geophysical Union the following papers in addition to the regularly scheduled committee report were presented relative to stream-dynamics studies: "The relation of suspended to bed materials in rivers," E. W. Lane and A. A. Kalinske; "Velocity-distribution in open channels," E. H. Taylor; "Studies of meandering of model-streams," Joseph B. Tiffany, Jr. and George A. Nelson; "Studies of the transition-region between laminar and turbulent flow in open channels," Lorenz G. Straub; "Some experiments on shallow flows over a grassed slope," W. O. Ree.

The Sub-Committee on Land-Forms under the chairmanship of Irving B. Crosby reports as follows:

"Members of the Sub-Committee on Land-Forms are carrying out a study of the lower Mississippi with the view to securing evidence of aggrading or degrading of the channel, and a study of the subject of stable channels of streams.

"The first study is being made by Gerard H. Matthes, who is carrying the study back into history about 50 years, as far as available data will permit. The results of the study so far point to the conclusion that the channel, as regards vertical movement, has generally remained within a foot or two of the same elevation with respect to sea-level throughout the period for which accurate data are available. This period includes conditions prior to as well as since the construction of the levee-system. Effective confinement of flood-waters to the river-channel has obtained since about 1920. Only great floods have succeeded in breaking through a few points.

"As a whole, the River gives no indication of having either aggraded or degraded. However, local aggrading is quite noticeable at a number of points, and this is traceable in all instances to obstructions or constrictions created incident to the settlement of the valley by man. In one case, the effects of aggrading are serious over a stretch of 60 miles, but this is exceptional, and not representative of the average case. The important point in this connection is to keep morphologic causes separate from accidental or artificial causes.

"The introduction of thirteen cut-offs in the reach from the mouth of White River to Angola, a river-distance of 400 miles, is causing the course of the River to become shortened by about

120 miles. As the engineering plan intends to preserve as nearly as practicable the original slopes of the River, a lowering of the River is in progress which is cumulative in an upstream-direction. This amounts to over 13 feet in the vicinity of Arkansas City and to over eight feet at the Mouth of White River. The full effect there has not yet been felt. Degrading of the River has been accomplished by the River's own forces, assisted only by dredging wherever erosion became delayed by resistant materials.

"The second study is being supervised by Professor E. W. Lane. In this study an investigation was made of the characteristics of the channels of the lower Mississippi and the St. Clair rivers to see how the shape of their channels agreed with the relations proposed by Gerald Lacey whose work has been widely accepted in India. The St. Clair River was used because of its particularly uniform flow. The study is not sufficiently far advanced at the present time to permit any conclusions."

On the program for the meeting this year are a considerable number of papers related to stream-dynamic problems. It is of special interest that five of these papers are concerned with the mechanics of sediment-transportation in open watercourses. An index of the activity in stream-dynamics is in part reflected by the bibliography covering some 670 references on stream-dynamics included in last year's report of a two-year review of literature.

Although it has been customary in this Committee's work to present a review of the literature bi-annually, this year an exception is made by the introduction of an intermediate report, because of the especially great activity in research relative to sediment-transportation and erosion. Publications have been so prolific that it is not unlikely that even a searching review of the literature will not be without oversight of some noteworthy work. This year the bibliographic review presented with this report relates only to sediment-transportation and related phenomena instead of the whole field of stream-dynamics.

Many writings on the hydraulics of sedimentation are of a random nature, but studies have been stimulated and many of the research-projects crystallized as the result of several specially scheduled conferences, all of which have not yet come to complete fruition. The publications of two important international conferences, meeting the latter half of 1938, have appeared in the past year; these refer to the Sixth Baltic Hydrological Conference held in Lübeck, Germany, August 15-20, 1938 [see 1 to 12 of "References" at end of report], and the Fifth International Congress for Applied Mechanics held at Harvard University and Massachusetts Institute of Technology, Cambridge, Massachusetts, September 12-16, 1938 [13]. At the Applied Mechanics Conference many problems of fluid mechanics and fluid turbulence were discussed in detail, and the mechanics of sediment-suspensions was given some consideration; while at the Baltic Conference numerous river-hydraulics problems were discussed, including stream-bed forms and sediment transportation by flowing water.

During the past year there were scheduled four conferences which brought forth numerous observations and treatments of the general problem of sediment-transportation by rivers and related occurrences. A number of papers were presented before the Section of Hydrology, American Geophysical Union, at the meeting of April 26-29, 1939 [14], another group at the Hydraulics Conference at Iowa City, sponsored by the Civil Engineering Division of the Society for the Promotion of Engineering Education and the Iowa Institute for Hydraulic Research, June 12-15 [15], and a number of especially noteworthy papers of interest by foreign observers [16-29] were presented at the meeting of the Commission of Potamology, International Association of Scientific Hydrology, held in Washington, September 4-15, 1939. At this same international congress there was held at the Hydraulics Laboratory of the Bureau of Standards a "Round-table discussion of the rôle of hydraulic laboratories in geophysical research" [30-37].

One of the general topics for discussion at the meeting of the Commission of Potamology was phrased as follows: "Studies of conditions under which solid material is transported in streams with movable beds, evolution of the bed form--formation of banks, bars, and holes, laws of transportation of material, especially with regard to the speed and depth of water, the specific weight and dimensions of materials, according to laboratory-tests and direct observation of natural streams." Countries presenting papers [16-29] include Belgium, Denmark, France, Germany, Great Britain, Italy, Latvia, Netherlands, Poland, Switzerland, United States, and United Socialist Soviet Union. The broad international scope is a fair index of the work being done in the field of the mechanics of sediment-transportation by flowing water. A discussion of the content of this imposing group of papers will be left for another time, when, it is hoped, they will be generally available as printed proceedings of the International Association of Scientific Hydrology.

Another meeting of international scope concerned especially with the general subject of sediment-transportation by rivers was scheduled by the International Association for Hydraulic

Structures Research, to have been held in Liege the latter part of September, 1939. This conference, of course, was nullified in consequence of the international tension which developed not long before the scheduled time of the meeting. However, considerable activity was stimulated in the field of river-hydraulics as related to sediment-transportation by virtue of the scheduled program. Symposiums were to be presented on "Bed-load transportation research" and "Scour below weirs."

River-model studies--In recent years the river-model has rapidly found an important place in hydraulic-laboratory work. Experiments are made on movable-bed river-models with a view of obtaining an experimental analysis of projected river-control structures. In the United States the United States Engineer Department, the Bureau of Reclamation, and the Soil Conservation Service have especially been concerned with work of this character; likewise the Tennessee Valley Authority and many university laboratories. With a view of crystallizing the fundamentals of this type of laboratory-research and to assist with the standardization of the present rather heterogeneous system of symbols and nomenclature the Committee on Hydraulic Research of the American Society of Civil Engineers is preparing a "Laboratory manual for hydraulic model studies" [38], now in a preliminary form.

Articles have appeared both in this country and abroad concerned particularly with the limitations of model experimental work. Thus, in a paper on "River physics laboratories of Europe and America" [39] a review is presented of the river-model experiments recently performed in Europe and America and their significance. Discussion is given of the tidal experiments on a model of the Severn River, German experiments on models of the Elbe, the Rhine, and experiments on models of the Mississippi, rivers of India, and others. The results of recent investigations at hydraulfc laboratories in Germany [40] are discussed, giving consideration to sediment-transportation, levee-construction, and the like.

The limitations of applicability of the results obtained from river-model studies have been discussed both in this country and abroad [41-46]. Questions for discussion involved the distortion of models with reference to depth, the use of granular material in models with lower specific gravity than the sand found in actual rivers, and many other points of interest. With the various types of distortion involved, it is well pointed out that rather than referring to "similarity" in models probably "corresponding" occurrences would be more appropriate. The verification of model-occurrences by comparing to the prototype have been all too infrequent, but some studies of this character are now being made. Thus, it has been found that the scour below a weir on the upper Rhine River, which had been designed with the aid of experimental analysis some ten years ago, showed a good agreement of the present conditions in nature with those observed in the river-model [47].

Other special studies with the use of models include sedimentation at the confluence of rivers [48], studies of meandering of model-streams [49], the resistance to flow of water along a tortuous stretch of river and in a small-scale model of the same [50], and the formation of sandbanks and sand-ripples with obstruction (piers and sills), bends, and contraction works [51]. Descriptions have been presented of new river-hydraulic laboratories [52] including what is called the first river-hydraulic laboratory of China [53].

Laboratory-studies of bed-load and suspended-load movement by flowing water--Some studies are in progress under idealized conditions of bed-load transportation by flowing water. A recent paper on this subject describes a laboratory-investigation of the problems of flume-traction and transportation [54]. Another paper related to this general problem describes experimental studies of the transportation of sand and gravel in a pipe-line [55]. Studies made abroad are reported, indicating the dependence of bed-load movement upon form of grain and temperature (therefore viscosity) of the water [56]. A striking result of this investigation is the great increase in sedimentary load with decrease in viscosity of the water, thus indicating that turbulence plays an important rôle in the mechanics of bed-load movement. Experimental studies have been made of the velocity of water and its erosiveness in sheet-erosion process [57].

Viscosity, of course, plays an important rôle in the movement of sedimentary material by suspension. Both practical and idealized discussions have been presented recently on this general subject. Papers have been given on suspended-load control and the problem of channel-stabilization [58], the hydrodynamical theory of the viscosity of suspensions [59], the motion of cylindrical particles in viscous flow [60], and a discussion of the flow of plastic and pseudo-plastic materials as compared with and in contrast to viscous flow [61].

The theory of turbulence as related to sediment-transportation by flowing water--The theory of fluid turbulence has developed rapidly the last several years and is now providing a possible

explanation and rational theory for the mechanism of sediment-transportation. Although much remains to be accomplished in this modern field of thought, several well-conceived discussions have been presented both in this country and abroad. Thus, using the kinetic theory of gases as a basis, differential equations have been developed for the suspended load of a stream in general, in a two-dimensional homogeneous stream, and finally in a turbulent stream [62]. Application of similarity-principles and turbulent research to bed-load movement as well as to suspended load indicates that a more general theory will eventually be developed with this approach [63-66].

It is now generally recognized that a theory of sediment-transportation by flowing water cannot be complete without consideration of fluid turbulence. A general theory, therefore, can become quite complex. Various approaches to the problem are now being proposed; some of them consider only bulk-factors, others consider the mechanism of internal turbulence in some detail. The practicing engineer prefers to deal with bulk-factors provided they give reasonably reliable results. A number of checks have been made on the more rational analysis involving consideration of mechanism of internal turbulence, and it is quite likely that a usable procedure will be developed as more data become available. Various approaches are well presented by a number of American and foreign papers which have appeared in the course of the past year [67-76].

Rivers, river-estuaries, and beach-erosion--Discussions of the behavior of rivers with particular reference to their sedimentary characteristics have been frequent. A study of the water- and sediment-movement in serpentined river-stretches was presented [77] and general fundamental principles for the regulation and improvement of an alluvial river [78]. Other papers include a study of solid-matter discharge in rivers with sandy beds [79] with particular reference to the Don River, also the Rhine in Holland [80], the Fyris River in central Sweden [81], the Yellow River of China [82], and others. A study of materials in suspension in the Mississippi River [83] and discussion regarding the effect of cut-offs in the lower River upon its regimen have appeared [84-87]. Other studies include silt-problems of Imperial Irrigation District as affected by completion of Boulder Dam [88], the deposition of sediment in reservoirs [89], and the functions of debris-dams [90].

Hydraulic-model studies have been made of harbor-problems [91-92] and the influence of sediment-movement in a tidal river [93]; other tidal-model experiments were in connection with the Rangoon River and the mouth-arms of the Irawadi River Delta [94].

The problem of beach-erosion has been discussed from the viewpoint of the engineer [95], giving a short geological, hydrographic classification of the coast of the United States of America, also the development and installation of laboratory-facilities for the investigation of wave-tanks on beaches [96]. Studies have been made regarding the inclination of the strand along sandy beach-shores [97-98], giving consideration to the principal direction of the wind and the mean grain-size of the material forming the strand. Other studies were made of erosion and sedimentation, that is, rise and fall of sand along the Ligurian Coast [99].

Miscellaneous studies, mechanical analysis of sediment--An especially comprehensive treatment of the general subject of sedimentation was presented as a symposium [100]; included are sections on transportation of detritus by moving water, effect of transportation on sediment-particles, etc. Another treatise on sedimentation appearing in 1939 presents a comprehensive discussion of the sources of sediment [101], the environmental factors that influence their production, transportation, and deposition, etc. Other reports include the measurement of sediment-discharge [102], observations of the influence of forest upon the soil and detritus-formation [103], silt-problems of the western part of the United States [104], and the report of the Committee on Dynamics of Streams of the American Geophysical Union containing an extensive bibliography covering a two-year period of literature appearing in various languages [105], referring in part to (a) investigations of regimen of rivers and bed-load studies, (b) mechanics of sedimentation, suspended load of rivers, density-currents, sedimentation in reservoirs, and (c) miscellaneous river-hydraulic studies involving sedimentation-problems.

A number of discussions have appeared regarding the classification and graphical representation of the mechanical composition of sedimentary material [106-109].

Concluding comments--The transportation of solid materials by moving fluid forms one of the most complex fields of hydraulic research. Thus, the vagaries in the behavior of rivers have long been and still are baffling to the most careful observers. The river-hydraulic laboratory is now aiding materially in the closer observation of sediment-transportation phenomena, for here some of the variables can be controlled and the observations made under more or less idealized conditions.

The various conflicting statements which have appeared from time to time in the past emphasize the importance of the careful observation in nature in order to establish more definitely the physical facts and provide a firmer basis for a mathematical approach. Certainly, detritus-motion is not yet clarified, either in its mechanics or in its practical aspects. However, the problem is further complicated by the difficulty of making reliable field-observations. Innumerable types of sediment-traps have variously been devised for making observations of the transportation of material along the stream-beds and others for determining amounts and character of the material transported in suspension. Studies are now in progress to ascertain the relative merits of these various devices.

The internal turbulence of a stream is now becoming generally recognized as of importance in the suspended-load distribution. Thus, the theory of turbulence is now being taken into account in the general theory of sediment-transportation. This increases the complexity of the analysis but should lead to focal points, eventually providing a better concept of the nature of the transportation-phenomena. Although this notion has been recently well crystallized for the part of the stream some distance above the bed, the mechanism of turbulence is still very vaguely understood in the immediate region of the stream-bed. Analytical treatments have been proposed regarding the forces on the individual stream-bed particle at impending motion. This latter problem must be further studied in the light of information regarding the laminar film boundary-layer.

Many topics have suggested themselves as timely for consideration of the Committee during the coming year. The Sub-Committee on Land-Forms will continue its research-studies. As a special feature of its program for next year it is contemplated to sponsor a symposium on sediment-transportation, possibly confining the papers to suspended load in view of the great activity in this particular field of research.

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SPECIAL COMMITTEE ON FLOOD-WAVES, 1939-40

Lorenz G. Straub, Chairman

The Special Committee on Flood-Waves is now in its third year of existence. Up to last year the work of the Committee has been carried on primarily through sub-committees and special assignments to individual members and their colleagues. These sub-committees having served their function and presented their reports were automatically dissolved. Two changes in membership of the Committee occurred during the past year; the membership is now as follows: Merrill Bernard, U. S. Weather Bureau, Washington, D. C.; M. C. Boyer, U. S. Geological Survey, Washington, D. C.; H. N. Eaton, Hydraulic Laboratory, National Bureau of Standards, Washington, D. C.; R. S. Goodridge, U. S. Soil Conservation Service, Washington, D. C.; G. A. Hathaway, Office of Chief of Engineers, U. S. Engineer Department, Washington, D. C.; Robert E. Horton, Consulting Hydraulic Engineer, Voorheesville, New York; Ivan E. Houk, U. S. Bureau of Reclamation, 440 Customhouse, Denver, Colorado; Hans Kramer, U. S. Engineer Office, Conchas Dam, New Mexico; F. T. Mavis, College of Engineering, Pennsylvania State College, State College, Pennsylvania; M. P. O'Brien,

College of Engineering, University of California, Berkeley, California; Lorenz G. Straub (Chairman), University of Minnesota, Minneapolis, Minnesota; H. A. Thomas, Carnegie Institute of Technology, Pittsburgh, Pennsylvania.

Attention is here called to last year's report of the Special Committee on Flood-Waves, and also that of the preceding year, in which are crystallized the results of the work of the subcommittees. Last year's report includes an extensive annotated bibliography on the general subject of flood-waves, prepared by a sub-committee under the chairmanship of Professor F. T. Mavis. There is also here included a report of the Sub-Committee on Current Investigations by Professor H. A. Thomas.

In addition to the papers and reports sponsored particularly by the Committee, there have been other reports and papers on flood-waves and related hydraulic occurrences which are of special interest. Thus, under the chairmanship of Merrill Bernard a symposium on floods was assembled and presented at last year's meeting of the American Geophysical Union [see 1 of "References" at end of report]. Another symposium, not yet published but which will be of special interest, is that presented on "The forecasting of floods, with special regard to observations of rainfall, of snow-cover, and of atmospheric conditions," at the Conference of the Commission on Potamology, International Association of Scientific Hydrology, meeting in Washington, September of 1939 [2]. Contributions to this symposium were presented by official representatives from many foreign countries, Belgium, Bohemia-Moravia, Canada, England, Finland, France, Germany, Italy, Japan, Poland, Union of Soviet Socialist Republics, and United States. Other papers at this international meeting that concerned flood-waves were given in a "Round-table discussion on the rôle of hydraulic laboratories in geophysical research," held at the National Bureau of Standards. Publication of these papers also is still pending.

A series of papers is now being prepared by the Hydraulic Laboratory Section, National Bureau of Standards, the first of which was published this year under the title "Mathematical theory of irrotational translation waves" [3]. The statuses of current laboratory-investigations on flood-waves are enumerated in a bulletin of the Hydraulic Laboratory Section, United States Bureau of Standards [4].

Some investigations are at present in progress by the United States Engineer Department and other Governmental agencies concerned with the improvement of flood-situations on natural water-courses. It is anticipated that reports will be available for presentation at next year's meeting of the Section of Hydrology concerning the progress of studies on river-courses.

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NOTES ON JOINT ROUND-TABLE ON RUNOFF AND INFILTRATION

W. G. Hoyt, Chairman, Committee on Runoff, and
G. W. Musgrave, Chairman, Committee on Infiltration

The all-day round-table held Saturday, April 27, 1940, was attended by 70 members of the Section of Hydrology of the American Geophysical Union, of which 57 attended a special luncheon. Federal agencies interested in hydrologic problems were well represented, especially the Forest Service, Soil Conservation Service, United States Engineer Department, Weather Bureau, and Geological Survey. In the introductory remarks, it was brought out that there was no clear line of demarcation between problems relating to runoff and problems relating to infiltration, and that it was fitting the two subjects should be discussed at a joint meeting. Early in the discussion it was pointed out that to be most constructive the group should recognize (1) what we know we know, (2) what we think we know, and (3) what we do not know.

In introducing the first subject for discussion, namely, questions with respect to the correlation of the infiltration-theory with stream-rises, the Chairman pointed out how closely the theory of absorption, percolation, and runoff as stated by Houk [Ivan E. Houk, Rainfall and runoff in the Miami Valley, Miami Conservancy District, Tech. Rep., Part 8, 1921] corresponded to the more recent theories of surface-runoff and infiltration and the desirability for present-day investigators to take full advantage, with credit, of the well-executed studies which have been made in the past. It was pointed out that as a result of the many observations being made on plots and small catchment-areas a wealth of information was being collected relating to the ground-phase of runoff, and that to be of the most practical value, these observations should be correlated with stream-flow and stream-rises, as such. The discussion brought out that there was still a considerable gap in our knowledge of just what happens from the time the rain-drop hits the ground until it appears as a part of the stream-rise which could not be entirely solved by a study of surface-runoff, as such. Discussion with respect to limitations of the infiltration-theory in relation to stream-rises was very extensive, especially its limitations in extensive areas in the United States where surface-runoff, as such, is generally insignificant. Discussion was continued along the second principal topic, namely, the extent to which stream-rises are made up of surface- and subsurface-flow.

The discussion brought out the point that in correlating the ground-phase of runoff with the channel-phase, there was no clear-cut boundary separating the water which appears in stream-rises and that which is retained in the ground, that in some areas the surface of the ground might be considered a boundary, in others a zone throughout the A-horizon, in others the B-horizon, and in other areas on or in the underlying rock-structure. An understanding of the problem apparently involves not only a knowledge of the rate of surface-runoff but also factual information regarding the capacity of the A- and B-horizons and the underlying rock-structures to retain water. The discussion brought out the many difficulties involved in correlating observations on small areas with basin-wide runoff, due to the absence of either homogeneous basin- or storm-characteristics.

Topics 3 and 4 related to the effect of volumetric changes in the zone of aeration on surface-runoff and subsurface storm-flow and correlation-factors between surface-runoff and ground-water runoff. There seemed to be considerable unanimity of opinion to the effect that quite definite relations might exist in many areas between the amount of water in the A- and B-horizons and the runoff-potentialities expressed either in terms of infiltration-capacity or in volume of stream-rise in relation to total rainfall. Difficulties which had been encountered in correlating soil-moisture in many kinds of soil with infiltration-capacities and probable reasons for correlation or lack of correlation were also briefly discussed.

The afternoon session following luncheon was devoted to a continuation of many of the topics discussed during the morning session and was concluded by discussion of the effects of snow, ice,

and frost on runoff-potentialities, which, although altogether too brief considering the importance of the subject, did enable several to present some much needed factual data.

Representatives of the United States Engineer Department, Weather Bureau, Flood-Control Advisory Committee, and other agencies discussed questions relating to the application of hydrologic theories to present-day problems. The informal discussion achieved its objective in that it enabled research-workers in specific fields to become acquainted with problems in other fields and more familiar with the runoff-infiltration problem.

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SALT-WATER INTRUSION IN THE CONNECTICUT RIVER

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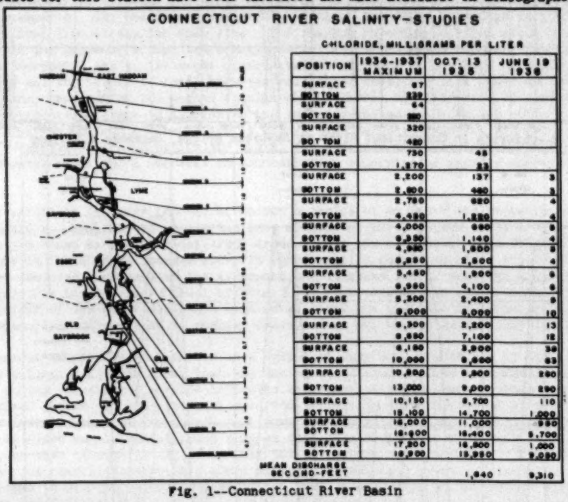
(Published with the approval of the Director, U. S. Geological Survey)

The intrusion of salt water in the lower Connecticut River Basin was studied during October 1, 1934, to June 30, 1939. The field- and laboratory-work was done as a project of the Works Progress Administration under the sponsorship of the State Water Commission of the State of Connecticut. Some technical assistance was given by the Geological Survey through cooperation with the State Water Commission.

Samples were collected from the River at a number of sections in the lower basin during October 1, 1934, to June 30, 1939. Most of the sampling was done at the Saybrook Highway Bridge and the results for this station have been tabulated and made available in mimeographed form



POSITION	1934-1937 MAXIMUM	OCT. 13 1938	JUNE 19 1938
SURFACE	67		
BOTTOM	339		
SURFACE	64		
BOTTOM	380		
SURFACE	320		
BOTTOM	480		
SURFACE	730	45	
BOTTOM	1,870	83	
SURFACE	2,200	137	3
BOTTOM	5,800	480	3
SURFACE	2,750	620	4
BOTTOM	4,480	1,220	4
SURFACE	4,000	880	5
BOTTOM	8,290	1,140	4
SURFACE	4,880	1,600	5
BOTTOM	8,220	2,600	4
SURFACE	5,480	1,900	6
BOTTOM	9,280	4,100	6
SURFACE	5,300	2,400	8
BOTTOM	9,000	5,000	10
SURFACE	6,300	2,200	13
BOTTOM	8,280	7,100	12
SURFACE	8,180	3,900	30
BOTTOM	10,000	8,800	63
SURFACE	10,800	6,800	280
BOTTOM	13,000	9,000	290
SURFACE	10,150	8,700	110
BOTTOM	12,400	10,700	1,000
SURFACE	16,000	11,000	950
BOTTOM	16,400	16,400	9,700
SURFACE	17,300	16,900	1,000
BOTTOM	19,200	19,210	9,290
MEAN DISCHARGE SECOND-FEET		1,840	9,310

Fig. 1--Connecticut River Basin

[Works Progress Administration for Connecticut Official Project 665-15-3-116, Bull. S-1, The salinity of the Connecticut River, October 1938; idem, Bull. S-11, The salinity of the Connecticut River at Saybrook Highway Bridge, June 1939]. Other results obtained during the study have been tabulated and copies of the tables placed in the files of the State Water Commission and the Geological Survey. This paper presents a brief summary of the results obtained during the study.

The average daily discharge for the Connecticut River at the lowest gaging-station (Thompsonville, Connecticut) during the three years ending September 30, 1937, was approximately 20,000 second-feet. Floods of considerable magnitude with a maximum mean daily discharge more than 15 times the mean daily flow occurred during the period of this study.

The maximum concentrations of chloride in the samples collected during the three years ending September 30, 1937, and the concentrations at a time of high-water slack on two days during this three-year period are shown in Figure 1. The stretch of the River covered was about 12 miles and observations were made at 16 stations between the Saybrook and East Haddam bridges. On a very few occasions the chloride at the East Haddam Bridge was high enough to affect the value

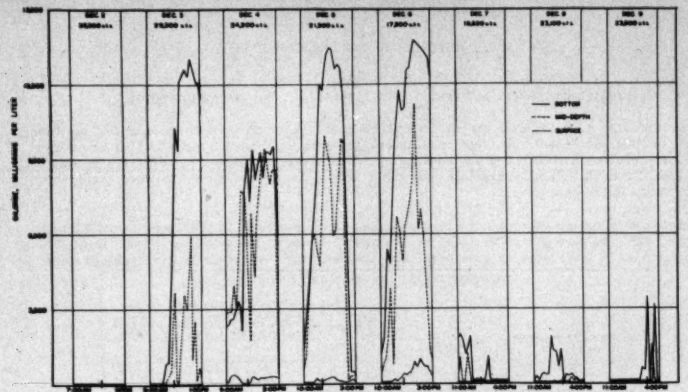


Fig. 2--Chloride in Connecticut River at Saybrook Bridge, December 2-9, 1937

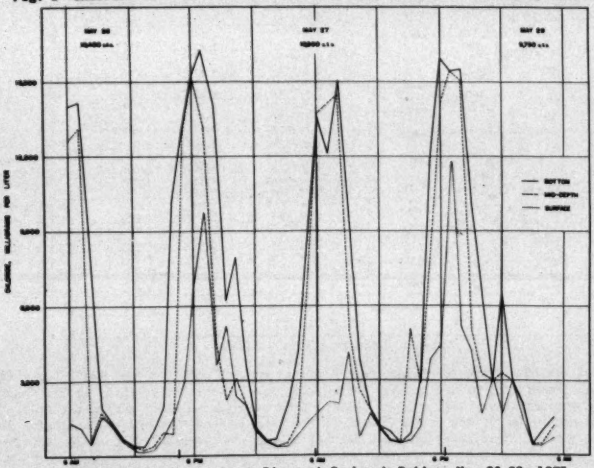


Fig. 3--Chloride in Connecticut River at Saybrook Bridge, May 26-28, 1935

for industrial purposes, but most of the time the river-water at all depths was satisfactory for all purposes as far down as Section W, eight miles below East Haddam. The extent of intrusion under two different conditions of river-stage is shown by the results given for the two days. For a river-discharge of 9,310 second-feet the maximum chloride at Section W (4.2 miles above Saybrook Bridge) was 13 parts per million.

The influence of river-discharge on the extent of intrusion of salt water is shown by the values given for the two single days in Figure 1. The influence of tidal action on the extent of intrusion is shown by the graphs in Figures 2 and 3. Special studies were made from time to time to follow the changes in concentrations of chloride at different stages on the River at a period of high tide and at a period of slack water following high tide. The results obtained on

these special studies showed that the concentrations of chloride were greater during the period of high-water slack than at high tide.

During this study the majority of the samples were collected at the Saybrook Highway Bridge, approximately 3.3 miles above the mouth of the River. Samples were collected at three depths, namely, surface, mid-depth, and bottom for different periods during the tidal cycle and on a few occasions during the entire tidal cycle or for a longer period.

The variations in chloride concentration throughout parts of the tidal cycle are shown in Figure 2. The results plotted in this Figure show the chloride-concentration at Saybrook Bridge for a period of eight days in December, 1937. On December 2 the river-discharge was sufficient to keep all salt water out of the section. On the next four days when the river-stage was falling the quantity of chloride showed a progressive increase. On December 7 a slight increase in the river-discharge forced salt water out of the lower part of the basin and apparently the effect was great enough so that on December 8 and 9 the maximum chloride-concentrations were much less than on December 4, although the river-discharge on December 8 and 9 was approximately the same as on December 4. The predicted time of high tide at the Saybrook Bridge is indicated by the short vertical line across the base-line. The maximum chloride occurred after high tide on December 2 to 6 and December 9, but the maximum chloride-concentration occurred shortly before high tide on December 7 and 8. It seems likely that an increase in the rate of discharge on December 7 and 8 was sufficient to force back the salt water resulting in a lower concentration of chloride on these days during the period of high-water slack. The intrusion of salt water in periods of low river-discharge is similar to the intrusion noted in December, but during periods of low discharge the maximum concentration is always considerably higher at all depths. On all occasions the changes in concentration are rapid, the increase of concentration occurring shortly after low-water slack and a decrease in concentration occurring as rapidly shortly after high-water slack.

The variations in chloride-concentration for a period of 48 hours are represented by the graphs in Figure 3. Samples were collected once an hour at three depths. The predicted times of high tide are shown by the vertical lines drawn across the base-line. The maximum chloride-concentrations in the surface-samples occur in those samples collected after 6 p.m. on each day. On these days the high tide came in the afternoon and it seems likely that the greater concentrations resulted from the increased tidal effects. The rapid changes in concentration of chloride after the periods of low-water slack and high-water slack are apparent in these graphs. The chloride-concentration is uniform in samples collected at all depths just before low tide.

Simultaneous samples were collected on a number of days during portions of the tidal cycle. Samples were collected in such a way that one bottle was filled at five to seven depths in one operation. During the studies samples collected at practically the same discharge on two or more days showed varied concentrations of chloride indicating that the mixing of fresh and salt water in the lower reaches of the Connecticut does not always take place in the same manner. The results obtained on the simultaneous samples show considerably lower concentrations in the surface-samples than in samples collected from the bottom or near the bottom. The concentrations in samples at intermediate depths vary under different conditions of river-discharge. The greatest changes in concentration occurred in the samples collected at the bottom after the period of low-water slack.

Summary--Graphs are presented showing the extent of salt-water intrusion in the Connecticut River Basin under different conditions of river-discharge and tidal action. Fresh water does not mix with salt water in the same manner under similar conditions of river-discharge.

The extent to which the surface-samples show an increase in chloride is dependent on the river-discharge and other factors.

U. S. Geological Survey,
Washington, D. C

SALINITY MOVEMENT AND ITS CAUSES IN THE DELAWARE RIVER ESTUARY

W. D. Mason and W. H. Pietsch

Water from the Delaware River has been used for domestic and industrial purposes since the shores of the River became colonized. The quantity of water used gradually increased, especially above the Delaware - Pennsylvania State Line. The users of the water in the zone between

this point and Philadelphia knew that brackish water moved up the River during periods of protracted low flow; however, the matter was not given serious consideration until 1930 when New York considered diverting water from the upper watershed. It was therefore imperative that the effect this diversion would have upon salinity encroachment be known. Coincidentally, there was protracted low flow during 1930 resulting in the worst salinity invasion of record.

The Delaware River Drainage-Basin has an area of approximately 13,500 square miles, half of which lies above the fall line at Trenton. The tidal estuary extends from Trenton to the sea, a distance of 130 miles, 25 miles of which, between Philadelphia and Trenton, has always been fresh water. The distance from Philadelphia to Artificial Island, 55 miles, is the marginal zone where brackish water moves up or down the River depending upon runoff. Below Artificial Island the Delaware Bay, which has a highly saline content, extends to the ocean (Figs. 1, 2, and 3).

A summary of stream-flow at Trenton where the River has been gaged for many years is as follows (drainage-area, 6,800 square miles):

Maximum yearly	= 16,600 cfs	(1927)
Maximum monthly	= 60,990 cfs	(March 1936)
Maximum day	= 250,000+ cfs	(October 1903)
Mean	= 11,416 cfs	(1907-1939)
Minimum yearly	= 7,800 cfs	(1930)
Minimum monthly	= 1,760 cfs	(October 1930)
Minimum day	= 1,450 cfs	(September 1932)

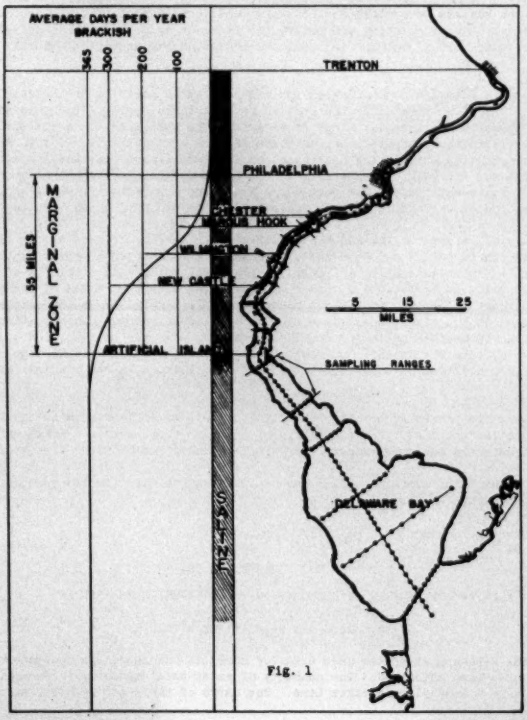


Fig. 1

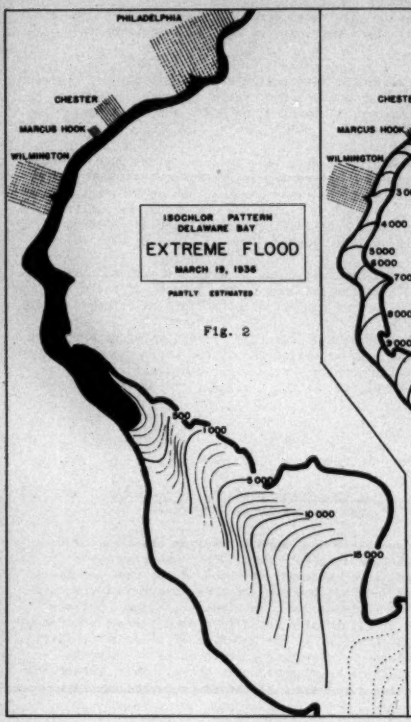


Fig. 2

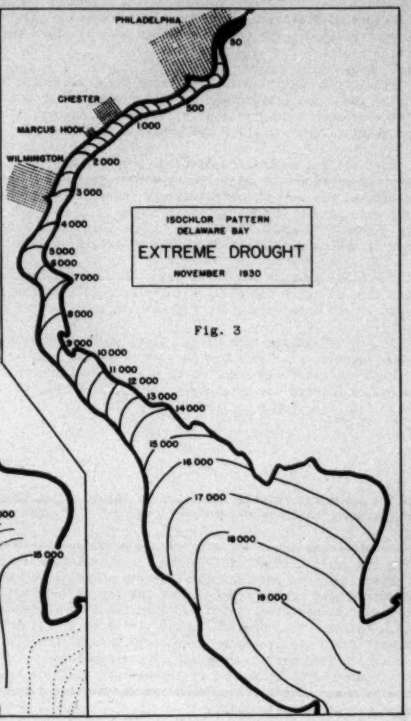


Fig. 3

The flow at Trenton is 65 to 70 per cent of the total into the marginal zone.

During the salinity invasion of 1930 our local interests organized the Delaware River Conservation Association largely for an investigation of salinity. About 2,000 samples were taken by cooperating industries during this period. The results, in a general way, outlined the salinity picture, yet they also emphasized the necessity for further study. A larger engineering research-group was immediately organized which included several nationally known consultants. Six launches were at once engaged, eventually securing over 10,000 quart-samples from all locations in the estuary. The present paper deals with an analysis based upon all results accumulated by the Association in 1930 and its Engineering Board in 1931 as well as many samples which have since been taken for further refinement of empirical data.

The chlorine-content of upland Delaware River water reaches a maximum of around 20 parts per million chlorine during periods of low flow unless contaminated by salinity or sewage. When salinity exists in the marginal zone, each variation in runoff changes, to some extent, the concentration throughout the estuary. Runoff added above the salinity-zone has a direct displacement effect, whereas the limited runoff entering the zone proper has a diluting effect. It is estimated that over 95 per cent of the runoff effecting salinity enters above the salinity-zone. These additions were the basic ones used in computations.

It was first assumed that many factors were essential, such as tidal heights, barometric

pressure, wind-direction, temperature of water and air, direction of current, evaporation, etc.; but, eventually, it was determined that many of these were without measurable bearing on salinity migration.

Tidal flow causes an absorption of fresh water by the brackish and the dilution of brackish water by the fresh, regardless of the stream-flow or direction of salinity movement, and the position of each concentration is dependent upon runoff entering the River above the lowest isochlor showing, unmistakably, the presence of sea water.

Vertical and transverse distribution of salinity at mean tide inthe marginal zone is comparatively uniform. As might be expected, salinity near the top is generally about ten per cent less than at the bottom. Transversely, concentrations increase about 15 per cent toward the Jersey side unless diluted by local runoff. These general conditions are of course altered by flood-waters throughout the year. It was found that satisfactory average results could be obtained by taking samples at mid-tide, mid-depth, and mid-channel.

The basic problem was to express the salinity-cycle in terms of displacement and it was observed that 50 parts per million chlorine indicated the presence of sea water. If the migrations of isochlor 50 were known, other concentrations showing higher salinity could be referred to it.

It was recognized that at all times there existed a volume (A) of fresh water between Trenton and isochlor 50. It was also clear that each day a portion (B) at the lower end of this pool of fresh water was absorbed by brackish water working upstream through tidal action. Stream-flow (C) for the area above this point furnished the third volume. These elements developed into the simple series

$$A - B + C = A_1$$

$$A_1 - B_1 + C_1 = A \text{ and so on.}$$

With the A volumes readily converted to points along shore, the position of the upper limits of brackish water could be determined, once the B or absorption volumes were known.

In preparing the diagram revealing B values, basic data were taken from observations made during the great drought of 1930 and from the intensive sampling in 1931. Observed movements of the upper limits of brackish water were plotted, as an average, in thousands of feet per day at the intersection of the average flow for the period, and the average cross-section of the movement. For illustration, Point No. 1 on Figure 4 includes the time element, 18 days, between March 8 and 29, 1931, when the upper limits of brackish water moved in a downstream direction at a rate of 1,900 feet per day, presumably brought about by an average flow of 11,944 cubic feet per second. This average rate was plotted against cross-section and stream-flow. Average cross-section was selected as it is believed that the average velocity occurs there, rather than at the half-way point. The distance-cross-section curve was later added to locate the various cross-sections geographically.

About 24 integrations were thus prepared, which, as shown on the chart, divide into two groups--plus for upstream advance and minus for downstream movement. From the division-line drawn between, we could closely approximate the zero-velocities at any point in the marginal zone. These stabilizing flows, converted from cubic feet per second to volume, provided the B-values for later combination with various stream-flow into any cross-section.

With the absorption values (B) determined, their combination with all possible stream-flow (C) against cumulative mid-tide volumes (A) from Trenton to Artificial Island presented a serious problem. To avoid the many thousand individual computations disclosing the course of salinity under all circumstances, a large-scale source-diagram (fragment Fig. 5) was constructed from which the elements were readily combined by manipulation. The auxiliary drawing consisted of a large-scale mid-tide volume-curve with channel-stations vertical and volume extending some ten feet horizontally. At each station, from Trenton to Artificial Island, the daily stream-flow needed to prevent salt movement was added to the mid-tidal volume, resulting in two roughly parallel curves. A movable celluloid scale, with second-feet equivalent to the volume-scale, completed the chart.

The operation disclosing daily reactions to any stream-flow was performed as follows: Zero on the movable scale was placed at the position of isochlor 50 on the lower or mid-tide volume-curve. The daily stream-flow was next selected on the scale and marked on the drawing. This point was then projected vertically to the outer curve representing the volume-plus-volume-of-

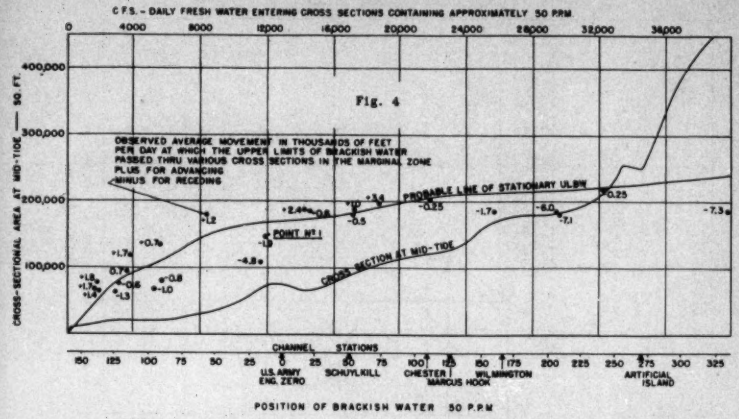
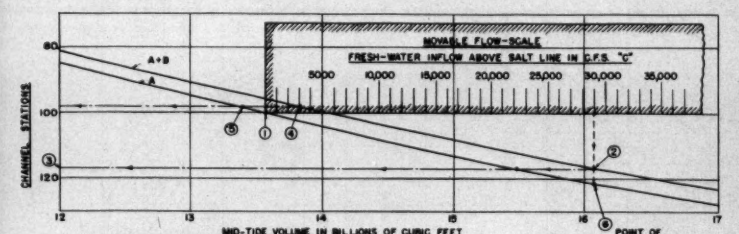


Fig. 4

daily-absorption. It is apparent that had the volume of runoff equaled the volume absorbed, the point would fall squarely on the volume-plus-absorption line, registering no change in the A-volume of fresh water when referred to the channel-station scale. Had the daily stream-flow exceeded the absorption (B), the point would fall beyond, or exceed, the outer curve and would lie directly above a point on this curve representing the excess of C over B when applied to the channel-station scale. With a flow less than the daily absorption, the point would lie between the two curves calling for an upward extension to the (A + B)-curve, thereby registering a loss to A of as many channel-stations containing the difference between C and B.

Movements caused by runoff in consecutive thousands were thus derived, starting at the limits of the marginal zone in each case and plotting all courses to the asymptotic vertices where the C amounts equal B (Fig. 6).

It is encouraging to note that small-scale diagrams may be used because, when salt movement



[EXAMPLE Nº 1 (1-2-3-6)

ELEMENTS:- UPPER LIMITS OF BRACKISH WATER AT
CHANNEL STA. 100 - DAILY FLOW ABOVE STA 100, 29,000 C.F.S. (2.54 B.C.F.)

MANIPULATION:- PLACE ZERO OF FLOW-SCALE AT STA. 100
1 DROP FROM 29,000 C.F.S. TO VOLUME PLUS ABSORPTION-CURVE
2 CHANNEL STA. 117 THEN LOCATES POSITION OF UPPER LIMITS OF BRACKISH WATER POINT (3)
A+C-B=A,

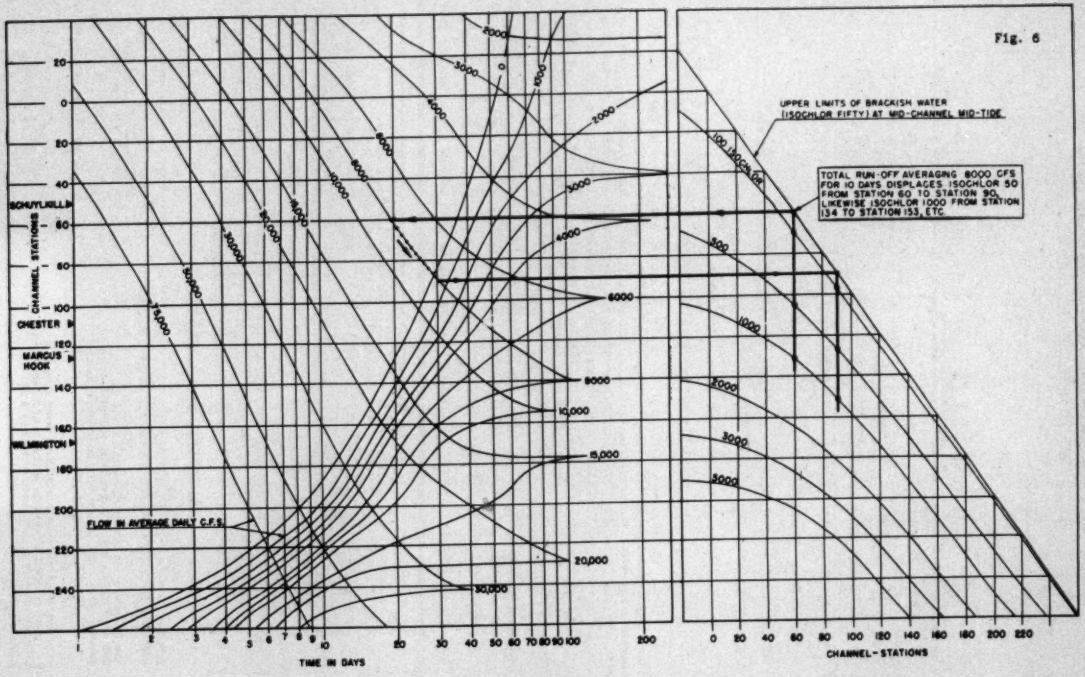
A= VOLUME ABOVE UPPER LIMITS OF BRACKISH WATER 13.56 B.F.C.
B= VOLUME ABSORBED BY BRACKISH WATER (.59 B.C.F. / 6800 C.F.S.)
C= VOLUME RUN-OFF ADDED (29,000 C.F.S. / 2.54 B.C.F.)
A= VOLUME OF FRESH WATER REMAINING (13.56 B.F.C. + 2.54 - .59 = 15.51) = CHANNEL STA. 117

[EXAMPLE Nº 2 (1-4-5)

A= 13.56 BILLIONS CUBIC FEET
B= .52 B.C.F. / 6000 C.F.S.
C= 3000 C.F.S. / .35 B.C.F.
A= 13.56 + .35 - .52 = 13.39 B.C.F. = CHA. STA. 98

Fig. 5

Fig. 6


UPPER LIMITS OF BRACKISH WATER (150CHLOR FIFTY) AT MID-CHANNEL MID-TIDE
TOTAL RUN-OFF AVERAGING 8000 CFS FOR 10 DAYS DISPLACES 150CHLOR 50 FROM STATION 60 TO STATION 90, LIKEWISE 150CHLOR 1000 FROM STATION 134 TO STATION 153, ETC.
CHANNEL STATIONS
SCHUYLKILL
CHESTER
MARCUS HOOK
WILMINGTON
FLOW IN AVERAGE DAILY C.F.S.
TIME IN DAYS
CHANNEL-STATIONS

is reversed, the accumulated errors in both personal element and errors in B are eliminated almost at once, as, had salt been charted too far upstream, the reversing increase in flow would cause a much greater recession to appear to take place. This action was well illustrated when a starting point in 1907 was found very successfully by assuming that the upper limits of brackish water were located at stations 100, 150, and 200. Using identical flow-figures, the courses converged practically to a point before 90 days' flow had been recorded.

The distance between the isochlors was ascertained by another large-scale plot from which the triangular section of Figure 6 was derived. On the working drawing, two channel-station scales were opposed and the median diagonal designated the upper limits of brackish water. Below the points of intersection for any two stations, observations indicating higher isochlors were plotted against the other scale. On this chart hundreds of titrations were spotted regardless of tidal stage, it being recognized that only the desired mean-tide relation could result when the smooth curves were drawn in.

The complete chart (Fig. 6), showing the interrelationship of the preceding steps, permits all operations to be made in a few seconds. Throughout the drought-season it has provided actual and anticipated river-concentrations each week since 1931. Calculated results usually coincide with the check-observations available. For example, both observation and calculation indicated that isochlor 50 was driven below Marcus Hook on August 20, 1933. For 370 days thereafter this isochlor shuttled back and forth a total distance of 135 miles before the charts showed its return to Marcus Hook, August 25, 1934. Samples taken that date verified the computations showing about 45 parts per million chlorine.

The stabilizing runoff figures for several communities are listed below:

Station	Total runoff in cfs required to halt isochlor 50	Station	Total runoff in cfs required to halt isochlor 50
Torresdale	2,000	Marcus Hook	7,200
Philadelphia	2,500	Wilmington	11,000
League Island	3,600	New Castle	16,600
Brammels Point	5,300	Artificial Island	45,000
Chester	6,600		

Without detracting from the validity of the formula, it is conceded that there are variable factors which at times deflect the isochlors from their normal position. Varying winds, rain-squalls, irregular evaporation, agitation of shipping, and dredging operations create currents and turbulence which singly or in combination frequently influence the position of the isochlors. Since all of these factors are transient, immeasurable, and unpredictable, they were disregarded and absorption-volumes were determined by comparing observed salinity with runoff only.

The average duration of salinity, as calculated from Figure 6, from 1907 to 1938, in excess of 50 parts per million has been as follows: New Castle, 201 days per year; Wilmington, 142 days per year; Marcus Hook, 57 days per year; Chester, 40 days per year; Philadelphia, 3 days per year.

This study has shown positively that when river-flow is known, salinity-conditions likewise may be known.

Sun Oil Company,
Marcus Hook, Pennsylvania

SALINITY OF THE LOWER SAVANNAH RIVER IN RELATION TO STREAM-FLOW AND TIDAL ACTION

William L. Lamar
(Published with the approval of the Director, U. S. Geological Survey)

Introduction

In order to obtain information needed in planning for industrial development along the Savannah River and in the city of Savannah, Georgia, a study of the salinity of the Savannah River was undertaken by the Geological Survey, United States Department of the Interior, in cooperation with the Georgia Division of Mines, Mining, and Geology. The Works Progress Administration of Georgia and the city of Savannah also cooperated in the study.

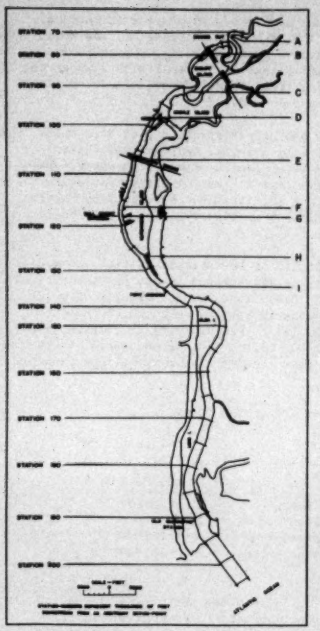


FIG. 1—LOWER SAVANNAH RIVER NEAR SAVANNAH, GEORGIA

The Savannah River lies on the boundary between the States of Georgia and South Carolina. The River proper from the mouth to the junction of the Tugaloo and Seneca rivers is 314 miles in length. The area of its watershed is about 10,579 square miles, of which 9,850 square miles are above the stream-flow gaging-station near Clyo, Georgia. The River is tidal for about 50 miles above its mouth. The average stream-flow for the Savannah River near Clyo, Georgia, was 10,410 and 10,820 second-feet, respectively, for the years ending September 30, 1938 and 1939. The city of Savannah, Georgia, located on the Savannah River 17 miles above its mouth, is an important seaport and industrial center. The lower Savannah River near the city of Savannah is shown in Figure 1.

Sampling stations--Sampling stations and river-locations are marked in thousands of feet in accordance with station-numbers established in connection with river-surveys. To simplify the identification of sampling and tide-stations, these stations were also marked with a letter beginning with "A" at the farthest upstream station.

During the investigation samples were collected at the sampling stations given below. In the following list of stations the numbers in parentheses preceding the plus sign refer to the station-numbers established in connection with river-surveys. They represent thousands of feet downstream from an arbitrary datum-point. Thus, sampling station A (72 + 700) is 72,700 feet downstream from the arbitrary zero datum-point. The base-station for this datum-point is station (100 + 000), which is at the lower end of Kings Island.

The sampling stations are situated at intervals in a stretch of the River from 3.2 miles below Bull Street to 8.6 miles above Bull Street, Savannah.

Station A (72 + 700) near Drakies Cut, 8.6 miles above Bull Street
Station B (78 + 200) at Atlantic Coastal Highway Bridge, 7.6 miles above Bull Street
Station C (89 + 500) at Atlantic Creosoting Company, 5.5 miles above Bull Street, (89 + 700) at Savannah Sugar Refining Corporation, 5.4 miles above Bull Street
Station D (98 + 000) at Savannah Cotton Factorage Company at Kings Island, 3.8 miles above Bull Street
Station E (106 + 900) at Seaboard Railway Bridge, 2.2 miles above Bull Street
Station F (116 + 600) at Herty Foundation Laboratory, 0.3 mile above Bull Street
Station G (118 + 300) at Bull Street
Station H (127 + 300) at lower end of the Atlantic Coast Line Railroad docks, 1.7 miles below Bull Street
Station I (135 + 300) at Fort Jackson, 3.2 miles below Bull Street

Tide-stations--Five automatic tide-gages were already being operated by the United States Army Engineers and the United States Coast and Geodetic Survey at points on the lower Savannah River. The locations of the tide-stations are marked in thousands of feet in accordance with station-numbers established in connection with river-surveys as previously explained in the location of sampling stations.

The tide-stations are situated at intervals in a stretch of the River from 13.6 miles below Bull Street to 5.5 miles above Bull Street, Savannah, at stations C, D, G, and I described above, and at Station J (190 + 300) at the old Quarantine Station 13.6 miles below Bull Street.

Curves for the five tide-gages showing changes in range and in half-tide level were similar in their general shape and trend and in this study gage-records of the tide-station at the old Quarantine Station were used.

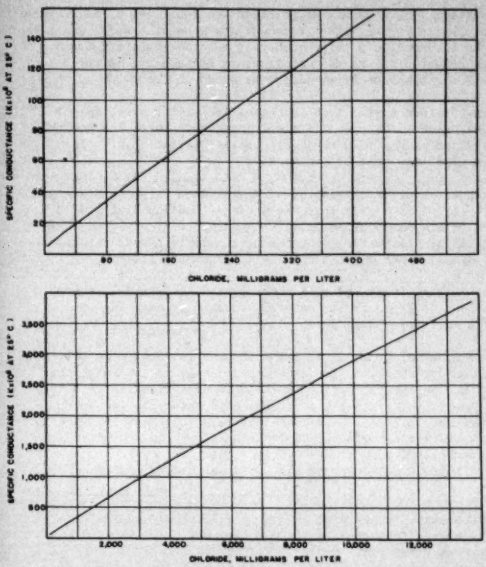


FIG. 2—SAVANNAH RIVER; SPECIFIC CONDUCTANCE-CHLORIDE RELATIONSHIP

Tide-characteristics [Marmer, H. A., condensed from "Tides and currents in New York harbor," U. S. Dept. Commerce, Coast and Geodetic Surv. Spec. Pub. 111, pp. 1-10, 1935]--The tide, the alternate rising and falling of the level of the sea, at most places occurs twice in a tidal or lunar day which on the average is 24 hours and 50 minutes. The rising and falling of the tide is accompanied by a forward and backward movement of the water. The term "tide" is used to designate the vertical movement of water and the term "tidal current" is used to designate the horizontal movement. The vertical rise and fall of the tide and the horizontal forward and backward movement of the tidal current are closely related, forming parts of the same phenomenon brought about by the tide-producing forces of the Sun and Moon.

The rise and fall of the tide at any place varies from day to day, generally in a periodic manner. This variation is mainly due to changes in the position of the Moon relative to the Earth and Sun. The three periodic changes in the position of the Moon relative to the Earth cause three variations in the rise and fall of the tides. The first periodic variation is related to the Moon's phase. At times of new Moon and full Moon, high waters rise higher and low waters fall lower than usual, and the range of the tide at such times is greater than the average. When the Moon is in its first and last quarters the tide does not rise as high or fall as low as usual.

The second periodic variation is related to the Moon's varying distance from the Earth as it moves around the Earth in an elliptical orbit. When the Moon is nearest the Earth the tides rise higher and fall lower than the average, and when the Moon is farthest from the Earth the tides rise and fall less than the average.

The third periodic variation is related to the Moon's declination. The Moon's declination is constantly changing since it moves in an orbit inclined to the plane of the equator. When the Moon is close to the equator the two high waters of the day do not differ much, and likewise the two low waters of the day do not differ much. When the Moon is close to either of the tropics the two high waters of the day differ in height and likewise the two low waters differ in height.

The month of the Moon's phases is approximately 29-1/2 days in length; the month of the Moon's distance from the Earth is approximately 27-1/2 days in length, and the month of the Moon's declination is approximately 27-1/3 days in length.

Tides as they actually occur vary widely from place to place. Meteorological elements will cause some variation in tidal movements. At times strong winds may cause marked variation. Stream-flow in a tidal estuary, such as the Savannah River, will affect tidal characteristics.

The variation in the tide from day to day produces a marked variation in the salinity of the water as will be shown later.

Expression of results--The salinity of the Savannah River water was indicated by measurement of the specific electrical conductance which varies with the amount and kind of mineral salts in solution. In order to keep a check on the results a large number of chloride determinations were made and correlation-curves were drawn up giving the relationship between the specific conductance and chloride content of the lower Savannah River water, as shown in Figure 2.

The specific-conductance results obtained during this investigation are reported as $K \times 10^5$ at 25° C, where "K" is the conventional symbol for specific electrical conductance and the expression "$\times 10^5$" means that the decimal point has been moved five places to the right. The term "at 25° C" means the results are given for that temperature.

Complete analyses of ten-day composites of daily samples of water taken from the Savannah River above all tidal influence for a period of a year indicate a range in conductivity of 3.6 to 5.9 and in chloride content of 1.6 to 3.0 parts per million. A conductivity of 20 is taken as a positive indication of the presence of salt water. For the Savannah River conductivity 20 corresponds to a chloride content of 42 parts per million or 42 milligrams per liter.

Tidal cycles--When there is a mixture of fresh and salt water present in a tidal estuary such as the lower Savannah River the concentration of the water is constantly changing with the rise and fall of the tide, producing a salinity tidal cycle.

Tidal cycles were run at stations A, B, C, D, E, G, H, and I in order to determine the approximate relation between concentration and stage of tide, and concurrently to determine the approximate time of occurrence of maximum salinity. During the tidal cycles, samples from top, middle, and bottom were collected at hourly intervals except at one hour before to two hours after tide changes when the samples were collected at half-hour intervals. Top samples were collected from the surface to two feet below the surface, middle samples were collected at mid-depth, and bottom samples were collected two feet above the bottom. The tidal-cycle studies generally covered a period of about 27 hours, thus covering the two tidal cycles that occur in a lunar or tidal day.

A study of the tidal-cycle curves brought out several points of particular significance. It was found that the maximum salinity occurs from shortly after to several hours after high tide. A number of elements such as stream-flow, tide, and wind affect the time of occurrence of maximum salinity in relation to the time of high tide. Also the location of the sampling station, the nature of the river-section, and the extent of salt-water intrusion will alter the time of maximum salinity in relation to the time of high tide. The maximum salinity of samples from top, middle, and bottom generally occurs in a short period time, but it does not necessarily occur in all three samples simultaneously.

The diurnal inequality of tides, the difference between morning and afternoon tides, will affect salinity movements in the manner that the higher high tide will produce a higher salinity than the lower high tide, except when changes in stream-flow are sufficient to prevent it.

Daily sampling at established stations--On December 1, 1937, regular daily sampling stations were established along the River at points selected from a preliminary survey. At these stations observations were made and samples were collected daily during the year ending November 30, 1938. These stations were also operated from July 21 to September 30, 1939, to check the computations made on salinity movements.

The daily sampling stations A, B, C, E, F, and H, were located at intervals in a stretch of the River from 1.7 miles below Bull Street to 8.6 miles above Bull Street, Savannah. At least one sampling station was maintained above the detectable limit of salt water. The samples were collected by observers at each sampling station.

Three sets of samples, each set consisting of one top sample and one bottom sample, were collected at each of the regular sampling stations each day at half-hour intervals, the sampling at each station thus covering a period of one hour. Top samples were collected from the surface to approximately two feet below the surface; bottom samples were collected approximately two feet above the bottom.

Sampling schedules provided for each observer each week were planned to include the time of maximum salinity during the daytime tidal cycle. The maximum salinity occurs at different times after high tide and the sampling schedules were modified from time to time as necessary to insure that the three sets of samples included a sample of maximum salinity.

Salinity profiles--The maximum conductivity-values found at the sampling stations each day were plotted against their location producing a graph that may be taken to represent the maximum salinity profile for the day (see Fig. 3). During the period of investigation a total of 426 salinity profiles were made. These salinity profiles were used to determine the daily position of conductivity 20 which was used as a basis for the salinity computations. For the Savannah River conductivity 20 corresponds to a chloride content of 42 parts per million or 42 milligrams per liter, as previously indicated.

The salinity profiles were also used to determine the daily position of conductivities 10 and 50 but these values were not used in this report.

Relation of salinity movements to stream-flow and tidal action--In studying the relation of salinity movements to stream-flow and tidal action the graph shown in Figure 4 was developed. Figure 4 gives the daily position of conductivity 20, stream-flow near Clyo, Georgia, and half-tide level at the old Quarantine Station for the year ending November 30, 1938. The stream-flow gaging-station is located at the Seaboard Railway Bridge near Clyo, above all tidal influence, 67 miles above the mouth of the River. The tide-station is located at the old Quarantine Station taree miles above the mouth of the River. The daily position of conductivity 20 was taken from the daily salinity profiles. The salinity movements on this graph show a marked variation with the half-tide level, particularly in the daily fluctuations in the position of conductivity 20. The general trend of the salinity movement is shown to be influenced mainly by river-discharge.

The movement of salinity as affected by the tide as shown in Figure 4 prompted further study for the development of a method whereby the cyclic variations in tidal intensities could be averaged in order to obtain a direct relation between stream-flow and salinity movements. The method used to obtain an average relation between stream-flow and the position of conductivity 20 was developed from a study of the curves given in Figure 5. Figure 5 gives the daily position of conductivity 20, five-day progressive average position of conductivity 20, stream-flow near Clyo, and range of tide at the old Quarantine Station. The five-day progressive or moving average position of conductivity 20 at any time is the average of the locations of conductivity 20 during the two preceding and two following days, as well as the current day.

On the lower Savannah River the tide-producing forces give rise to a semimonthly and monthly cyclic variation in tidal range and the five-day averaging of the positions of conductivity 20 tends to produce a fairly smooth cyclic curve that can be correlated with the tidal-range curve.

Stream-flow is the important factor influencing the general trend of salinity movements. In many cases, except when the River is in flood, the daily fluctuations and the semimonthly and monthly cyclic changes in salinity movements are largely due to tidal variations. On the lower Savannah River tidal intensities generally vary from day to day in a semimonthly and monthly cyclic manner and, therefore, an average relationship between stream-flow and the position of a given degree of salinity can be determined for the semimonthly and monthly periods which cover the variations of the tidal-range cycle.

In order to show more clearly the relationship of salinity movements to stream-flow and the tides a three-month section (January 1 to March 31, 1938) of Figure 5 is shown on an enlarged scale in Figure 6. This Figure particularly shows that variation in tidal intensities from day to day cause variation in the position of conductivity 20 and that by selecting periods covering the semimonthly and monthly tidal range cycle an average relationship can be obtained between river-discharge and the position of conductivity 20.

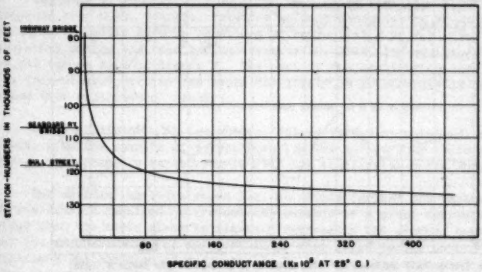


FIG. 3—SAVANNAH RIVER; SALINITY-PROFILE FOR APRIL 1, 1938

The average relationship between river-discharge and the position of conductivity 20 was determined by the following method: (1) Periods

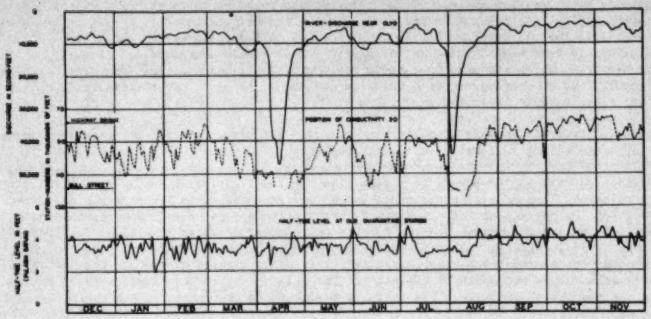


FIG. 4.—DAILY POSITION OF CONDUCTIVITY 20, STREAM-FLOW, AND HALF-TIDE LEVEL, SAVANNAH RIVER, YEAR ENDING NOVEMBER 30, 1938

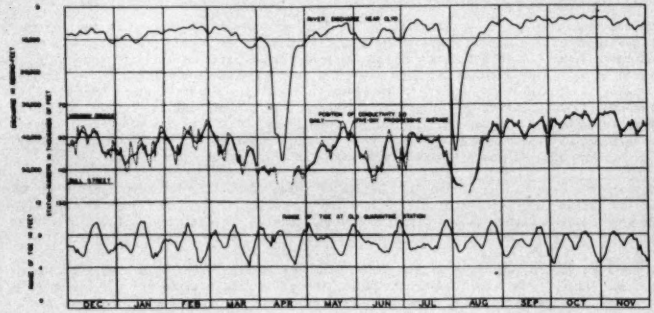


FIG. 3.—POSITION OF CONDUCTIVITY 20, STREAM-FLOW, AND RANGE OF TIDE, SAVANNAH RIVER, YEAR ENDING NOVEMBER 30, 1938

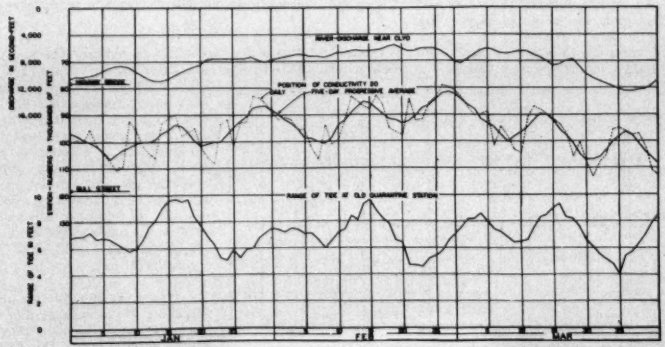


FIG. 6.—POSITION OF CONDUCTIVITY 20, STREAM-FLOW, AND RANGE OF TIDE, SAVANNAH RIVER, JANUARY 1 TO MARCH 31, 1938.

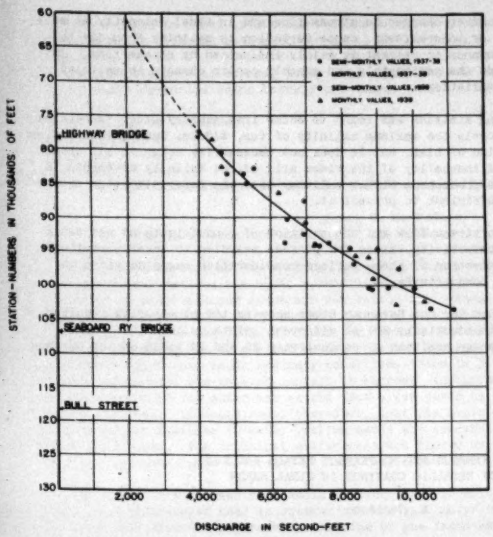


FIG. 7.—POSITION OF CONDUCTIVITY 20 AS RELATED TO STREAM-FLOW

were chosen to cover variations of the tidal-range cycle; (2) consideration was given to the river-discharge and the position of conductivity 20 in making the selection of the above periods.

Thus, for example, the period January 18 to 31, 1938, was selected. For this period covering 14 days the average river-discharge was 8,210 second-feet and the average position of conductivity 20 was Station (94 + 450). The next period selected was February 1 to 15, 1938. For this period covering 15 days the average river-discharge was 7,250 second-feet and the average position of conductivity 20 was Station (93 + 700). Similarly, periods were selected for the whole sampling year ending November 30, 1938, except when the River was in flood. Additional points were also obtained by selecting approximate monthly periods that included variations of the monthly tidal-range cycle. As an example, the period February 7 to March 9, 1938, covering 31 days was selected. For this period the average river-discharge was 6,970 second-feet and the average position of conductivity 20 was Station (90 + 750). All values obtained for selected periods were plotted in Figure 7, giving the equilibrium-curve for conductivity 20.

The effects of river-discharge and tides as recorded at one point and influencing salinity movements at another point involve a period of lag. The nature of this lag might be quite complex and variable depending upon the change or combination of changes in the forces involved. In general the method of averaging compensated for the lags involved.

When there are very large and sudden changes in river-discharge as when the River is in flood the movement of salinity is due mainly to river-discharge. However, salinity-movements during flood-periods will not be considered in this paper.

Position of conductivity 20 as related to stream-flow--Figure 7 shows the stream-flow as recorded near Clyo, Georgia, required to hold conductivity 20 at different points on the River. In order to obtain average positions of conductivity 20 for river-discharges lower than those occurring during the year ending November 30, 1938, the equilibrium-curve was extended as shown by the broken line in Figure 7. The part of the equilibrium-curve shown by the broken line is the interpolated portion and would not likely be as accurate as the portion of the curve determined from experimental results.

As an application of the method, values were also obtained, except when the River was in flood, from the results of sampling during the period July 21 to September 30, 1939. These values were found to agree closely with the equilibrium-curve shown in Figure 7.

The equilibrium-curve shows that at points farther and farther upstream progressively less stream-flow is required to prevent the advance of a given degree of salinity. It must be understood that the curve given in Figure 7 represents the average position of conductivity 20 and not the exact location at any particular time. The forces controlling salinity movements will fluctuate the position of conductivity 20 through this average position. It should be understood that the position of conductivity 20, as given in this report, is based on the maximum salinity occurring each day.

Summary--In the lower Savannah River changes in stream-flow and in tidal intensity as well as other forces, more or less minor or intermittent, cause variation in salinity from day to day. The general trend of saline advance or retreat is mainly influenced by stream-flow. In many cases the daily fluctuations and the semimonthly and monthly cyclic changes in salinity movements are due largely to tidal variations.

Maximum salinity at all sampling stations was found to occur from shortly after to several hours after high tide. In a tidal cycle the maximum salinity of top, middle, and bottom samples generally occurs within a short period of time, but it does not necessarily occur in all three samples simultaneously. The diurnal inequality of the tides will affect salinity movements in the manner that the higher high tide produces a higher salinity than the lower high tide except when changes in a stream-flow are sufficient to prevent it.

An average relationship between stream-flow and the position of conductivity 20 was determined by calculating discharge-isoconductivity values for periods selected to cover variations of the tidal-range cycle. In the selection of these periods consideration was also given to river-discharge and the position of conductivity 20.

An equilibrium-curve was obtained for the Savannah River showing the stream-flow required to hold a given degree of salinity (conductivity 20) at different points on the River. The equilibrium-curve represents the average position of conductivity 20 and is based on the maximum salinity occurring each day.

U. S. Geological Survey,
Washington, D. C.

CORROSION OF FERROUS AND NONFERROUS METALS AND THE BEHAVIOR OF METALLIC COATINGS IN TIDAL MARSH

I. A. Denison

(Abstract)

The characteristic features of tidal marsh from the standpoint of the corrosion-process are marked deficiency of oxygen, extreme acidity, and the presence of sulfides and of sea water. Because of the condition of deoxidation that prevails in tidal marsh, differences of potential on metal surfaces are necessarily small. This is offset, however, by the very low resistance of the corrosion-circuits.

The experimental data available for study of corrosion in tidal marsh consist of measurements of loss of weight and depth of pits on specimens of a variety of materials which have been removed biennially from two test-sites over periods of eight to ten years.

The common ferrous materials corrode rapidly in tidal marsh with little change either in the rate of pitting or of loss of weight with time. Because of the solubility of ferrous corrosion-products in this environment, protective films or deposits do not form in close contact with the corroding surface as is the case in well-drained soils.

The addition of chromium to steel reduced the loss in weight but concentrated corrosion in local areas with the result that the depth of pits on specimens of high-chromium steels were greater than on ordinary steel. The addition of nickel up to eight per cent to high-chromium steel did not entirely prevent pitting.

Both copper and zinc corrode appreciably in tidal marsh. The alloys of these metals, however, are more resistant to corrosion, the rate of corrosion of the low-copper brasses being practically negligible. This is contrary to the behavior of similar materials exposed to other types of soil in which specimens of copper and high-copper brass were corroded least.

Lead is very resistant to corrosion in tidal marsh. Corrosion produced by organic acids in soils is prevented in tidal marsh, probably by the formation of protective films of lead chloride and sulfate. Although highly resistant to corrosion in tidal marsh, lead does not provide effective protection for steel. Since the lead coatings were not entirely free from pores or pinholes, galvanic action resulting from the difference in potential between lead and steel resulted in the formation of pits on the coated specimens which were deeper than those on specimens of bare steel.

Zinc applied to steel as a thick coating entirely prevented the formation of pits in the underlying metal although both zinc and steel are corroded in tidal marsh. It is probable that the cathodic current-density on the areas exposed by corrosion of zinc was sufficient to maintain the potential of the exposed alloy layer approximately equal to that of the outer zinc-layer, further corrosion being thereby prevented.

National Bureau of Standards,
Washington, D. C.

THE CONTAMINATION OF GROUND-WATER BY SALT WATER NEAR PARLIN, NEW JERSEY

Henry C. Barksdale
(Published with the approval of the Director, U. S. Geological Survey)

The classic studies of Badon Ghyben [see 1 of "References" at end of paper] and Alexander Herzberg [2] that defined the basic principles governing the relation between salt water and fresh water in water-bearing sands are now fairly well known. They showed that fresh water floats on the heavier salt water and that, under static conditions, the ratio between the head of the fresh water above mean sea-level and the depth of the contact between fresh and salt water below mean sea-level, is determined by the relative specific gravities of the two waters. Other studies have shown that under ordinary conditions there is little mixing between the fresh and salt waters, so that the zone of contact is narrow. Instances have been observed in which the chloride-content of the water has ranged from a few parts to several thousand parts per million within a few feet. It would seem, therefore, that the basic conditions under which fresh and salt water occur together in water-bearing sands are somewhat similar to those in the tidal estuaries of streams. The principal differences are caused by the frictional resistance of the sand which prevents rapid movements of both fluids and probably retards their mixing.

When water is withdrawn from wells tapping sands in which fresh water and salt water are in contact, the fresh-water head is lowered and the salt water rises as far as the lowered fresh-water head will permit. A permanent lowering of the fresh-water head amounting to only one foot would permit salt water of the concentration of average sea water to rise about 40 feet. A less-concentrated solution would rise a greater distance. It is apparent, therefore, that extreme caution must be exercised in the development of fresh-water supplies from sands that are exposed to salt-water intrusion. Although these facts are now becoming increasingly well known to hydrologists and engineers, far too little attention has been paid to them in the past and there are many coastal areas in which good water-bearing sands have been contaminated by salt-water intrusion, or in which salt-water contamination appears to be imminent because of geologic and hydrologic conditions.

Although the advance of salt water can often be predicted, only occasionally is there opportunity to observe its advance. All too frequently the active wells are so near the shore that salt water appears in them with very little warning. It has been particularly noteworthy, therefore, to observe the advance of salt water into the so-called No. 1 sand near Parlin, New Jersey. Here the active wells are two or three miles from the source of the salt water and for more than two years it has been possible to observe the changes in salinity at several key-localities by means of samples collected periodically from test-wells.

The locations of the wells and of the tidal streams from which the salt water is entering the sand are shown on the map in Figure 1. The geologic features that affect the movement of the salt water are shown in Figure 2.

It will be noted that the situation in this area is unusual in that the salt water has gained access to the sand at points up the dip from the pumped wells. Only the wells at or near Runyon are directly down the dip, but the other wells encounter the sand at points lower than the salt-water intake. Originally the fresh-water head in the area just northeast of the town of South River was high enough to cause wells to flow at the surface. Therefore, fresh water must have flowed out into the bottom of the River if any holes existed in the impermeable river-fill material through which the river-channel is cut. Increased pumping and the deepening of the channels for navigation both occurred in the years between 1925 and 1935, and together they caused the major intrusion of salt water.

A report by the writer published in 1937 [3] showed that in some places the fresh-water head in the sand had been lowered as much as 110 feet, to altitudes as much as 70 feet below sea-level, and that the Washington Canal, which was dredged in 1929 to shorten the route of

barges traversing the South River, had penetrated sands connected with the No. 1 sand. The report suggested that probably salt water was entering the sand through the canal-bottom and recommended test-wells between the canal and the well-fields to check this assumption. A group of test-wells, drilled in the fall of 1937 and early in the winter of 1938, showed that the salt water had advanced toward the wells to an alarming extent. The location of the wells in this area and contours of chloride-concentration representing the probable extent of the advance of salt water into the sand are shown in Figure 1.

An industrial well near the site of well 27 was abandoned in 1930 because of its salt content. At that time the trouble was supposed to have been due to a leak in the casing of the

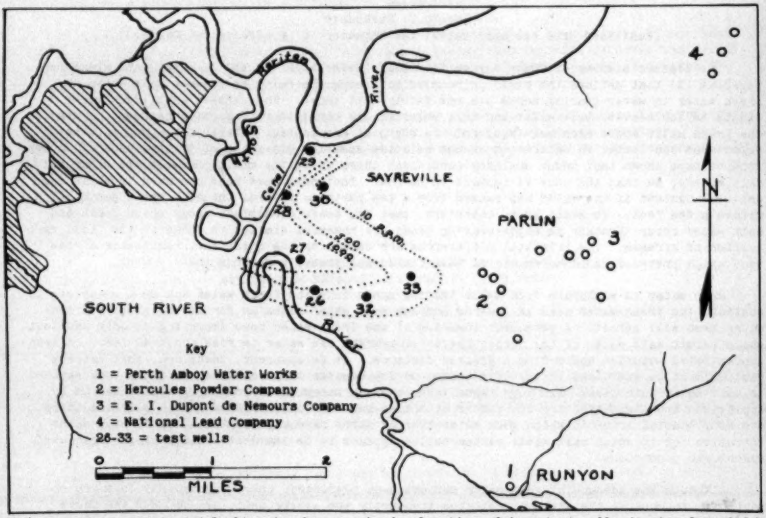


Fig. 1--Map of vicinity of Parlin, New Jersey, showing location of important wells drawing from No. 1 sand, of test-holes to the sand, and, by contours, of probable extent of salt-water intrusion into sand [intake-area of sand is indicated by shading, pumping wells by open circles, test-wells by filled circles]

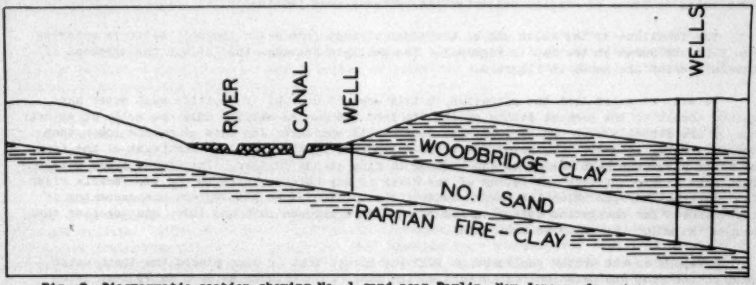


Fig. 2--Diagrammatic section showing No. 1 sand near Parlin, New Jersey, from intake-area to pumping wells [impermeable river-fill indicated by cross-hatching]

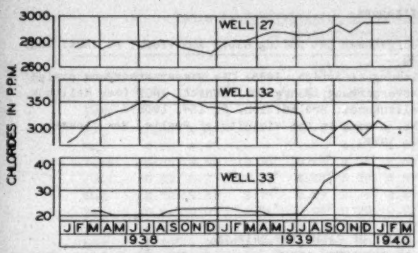


Fig. 3--Graph showing fluctuations of chloride-content of samples of water from wells 27, 32, and 33, January 1938 to February 1940

well. A sample from the same well in 1932 contained 300 parts per million of chloride. Samples collected from well 27 during 1938, 1939, and 1940 have ranged from 2,700 to 2,950 parts per million of chloride. The salinity of the water in the sand at this point is therefore about ten times as great as it was eight years ago. In 1938 water containing more than 300 parts per million was obtained from well 32, indicating that salt water of this concentration had advanced about a mile in six years.

The chloride-contents of samples of water from three of the test-wells are shown in Figure 3. Well 27 has already been discussed. Well 32 is about a mile from any possible point of intake and the fluctuations of chloride in the water from it therefore represent changes in the salinity of the water that is moving down toward the pumped wells. The decrease in chloride-content in well 32 in 1938 and 1939 may have been caused by a period when the water entering the sand was freshened by floods or when the rate of pumping was lowered and the higher head permitted less salt water to enter the sand. The chloride-content of water from well 32 now appears to be resuming its upward trend.

Well 33 is the test-well nearest to the well-fields at Parlin. It will be noted that the chloride-content of the water from this well fluctuated just above 20 parts per million from early in 1938, when the well was completed, until July, 1939. It increased to almost double its former value between July and November, 1939. The behavior of the chloride in the samples from this well is indicative of the rapidity with which the salt-water intrusion may be expected to occur when it reaches the pumped wells. The wells at Parlin are now yielding water containing from two to four parts per million of chloride and some of the industrial processes for which it is used cannot tolerate as much as ten parts per million.

The records from these wells seem to indicate that the salt water is advancing through the sand toward the pumped wells in waves of high salinity followed by somewhat lower salinity. This tendency is more or less evident in all three wells. As long as the pumping is continued each crest will probably be higher than the one before it, because water of higher salinity found near the salt-water intake will be drawn toward the pumped wells.

The old well near the site of well 27 flowed at an altitude of several feet above sea-level, until about 1927. At that time the total pumpage from the sand was about 4,000,000 gallons daily. The pumpage increased irregularly until it exceeded 9,000,000 gallons in 1935. The salt-water intrusion thus appears to have been caused by a lowered fresh-water head combined with the creation of a channel of easy access for the salt water through the bottom of the canal which was dredged about 1929. It also seems probable that some salt water entered the sand through the bottom of the South River where it passes near the exposed intake area or where its channel may have been cut through the impermeable river-fill.

In most of the area shown on the map (Fig. 1), the sand is covered by a layer of clay so that salt water cannot escape except through wells or through the areas where it entered the sand. If some means could be devised to shut out any additional salt water it might be possible to remove the salt water that is already in the sand by pumping and thus to restore the usefulness of the sand.

There can be no doubt that the problem of salt-water intrusion is becoming more serious at many places along the coast. Ground-water hydrologists have come to realize that in some localities the safe yield of an aquifer may be limited more by the danger of salt-water intrusion than by its capacity to absorb and transmit water. Unless effective control of the withdrawal of ground-water can be accomplished, grave permanent damage may be done to many of our water-bearing sands. There are serious legal difficulties in the way of effective control, particularly in the East, but as the need for regulation becomes more evident, these difficulties will no doubt be overcome.

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[2] Alexander Herzberg, Gutachten für dee Regierung in Aurich, 1886: Die Wasserversorgung einiger Nordseebäder, J. Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich, 1901 (see Keilhack, Konrad, Lehrbuch der Grundwasser- und Grellenkunde, 3rd edition, p. 134, 1935).
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U. S. Geological Survey,
Washington, D. C.

REPORT ON EXPLORATORY STUDY OF RAIN-GAGE SHIELDS AND ENCLOSURES AT COSHOCTON, OHIO

H. S. Riesbol

Several types of shields and enclosures were installed on standard non-recording United States Weather Bureau type rain-and-snow gages near Cosnocton, Ohio, during the summer of 1937. The study as originally set up was entirely exploratory in nature, that is, to determine the relative feasibility, ease of operation, cost of installation, and maintenance of the various shields and enclosures, rather than to evaluate precisely their effects upon the catch of the rain-and-snow gage. It was hoped that the study would point out one type of shield or enclosure as being most suitable for installation on the large number of rain-gages located on the watersheds being studied by the Hydrologic Division of the Soil Conservation Service, United States Department of Agriculture.

A preliminary report concerning the first five months of record from experimental gages MA to MH, inclusive, and Met. R was presented in the Transactions of the American Geophysical Union, Nineteenth Annual Meeting [see 1 of "References" at end of paper]. Since that time, gages MI, MJ, and MK have been added to the group, and it is believed that sufficient information is now available to justify closing the exploratory study.

The history of the exploratory study, together with a general comparison of the gages equipped with various shields and enclosures, may be grasped by inspection of Tables 1 and 2 which present monthly totals of precipitation in inches for the years 1937 to 1939. The missing records from gage MA for the months of March to May, 1938, are explained by the removal of the original installation in March and its reinstallation at a point 100 feet southward in May. Missing records from gages MC, MD, MF, MG, and MJ all occur during the winter months of November to March due to inability of these gages to measure snowfall.

A study of floods and soil-erosion is more concerned with the rains of unusual volume and intensity than with those of ordinary characteristics. These more severe storms are usually accompanied with driving winds which tend to greatly decrease the accuracy of catch of individual gages in exposed locations. In order to study the activity of the experimental gages under such conditions, their catch for all storms exceeding 0.75 inch is presented in Tables 3, 4, and 5 for the years 1937, 1938, and 1939, respectively. The lower limit of storm-magnitude was selected on a purely arbitrary basis, so that it would exceed the average storm, which is approximately 0.40 inch on the North Appalachian Experimental Watershed, and yet not include an excessive number of observations. Careful attention was given to the action of the various shields and enclosures under snowfall. Records from all the gages for all snowstorms during the years 1938 and 1939 are presented in Table 6. The receivers were removed from all the non-recording gages during these months and the receiver-funnel was removed from the recording gage.

Since only one of each of the various experimental types of shields and enclosures was installed in the exploratory study, no detailed statistical study has been made to determine mathematical significance of the rainfall-measurements. The regression-coefficient for the catch of each gage, as computed from a standard base, presents an interesting basis of comparison. The use of the mean catch from all the gages was at first suggested as a standard base, but did not appear to be feasible because of the frequency with which the number of gages used to form the mean was varied. This was due to the removal of some gages during the winter months, to the belated addition of new types to the study, to the change in location of a gage, and, in some cases, to faulty records. It was decided, therefore, that one of the gages should be selected as the standard base. This at once suggested gage MB, which represents the standard type of field-installation used in the watershed-studies.

Table 1--Precipitation by months for gages having various types of shields and enclosures, 1937 and 1938

Month	Catch of each gage in inches												Mean
	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	Met. R	
1937													
Apr.	5.06*	4.86	-----	-----	4.85	5.11*	4.90*	-----	-----	-----	-----	4.46	4.87
May	4.60	4.45	-----	-----	4.43	4.80*	4.62*	4.91*	-----	-----	-----	4.37	4.60
June	8.80	8.56	10.33*	10.93*	8.71	9.60*	9.39*	9.46*	-----	-----	-----	8.29	9.34
July	5.86	5.73	6.77*	6.43*	5.99	6.59*	6.32*	6.05	-----	-----	-----	5.77	6.17
Aug.	2.70	2.63	2.78*	2.58	2.74*	2.64	2.60	2.92*	-----	-----	-----	2.67	2.70
Sep.	0.94*	0.90	0.94*	0.93*	0.90	0.92*	0.86	0.94*	-----	-----	-----	0.87	0.91
Oct.	4.13*	4.03	4.21*	3.80	3.96	4.30*	4.12*	4.09*	-----	-----	-----	3.89	4.06
Nov.	1.40*	1.26	1.48*	1.43*	1.33	-----	-----	1.37*	-----	-----	-----	1.29	1.36
Dec.	3.49*	3.34	3.66*	-----	3.21	-----	-----	3.40*	-----	-----	-----	3.11	3.37
1938													
Jan.	2.37*	1.87	2.23*	-----	1.87	-----	-----	2.18*	-----	-----	-----	1.75	2.04
Feb.	2.74*	2.41	-----	-----	2.47	-----	-----	2.76*	2.58*	-----	-----	2.37	2.56
Mar.	-----	6.65	7.18*	7.24*	6.80	7.20*	6.92	7.17*	6.69	-----	-----	6.58	6.94
Apr.	-----	3.92	4.29*	4.20*	3.90	4.13*	4.00	4.09*	4.00	-----	-----	3.89	4.05
May	-----	5.15	5.64*	5.39*	5.26	5.42*	5.24	5.47*	5.22	5.53*	-----	5.15	5.35
June	4.23	4.30	4.62*	4.29	4.27	4.57*	4.46*	4.61*	4.31	4.47*	-----	4.27	4.40
July	2.31	2.25	2.46*	2.30	2.31	2.37*	2.29	2.31	2.29	2.35*	-----	2.22	2.31
Aug.	4.57	4.47	4.70*	4.59	4.59	4.90*	4.85*	4.76*	4.60	4.75*	-----	4.59	4.67
Sep.	3.07*	2.89	3.19*	2.89	2.96	3.04*	2.91	3.06*	2.97	3.07*	-----	2.88	2.99

* = Catch for gage exceeded mean catch of all gages for month.

Table 2--Precipitation by months for gages having various types of shields and enclosures, 1938 and 1939

Month	Catch of each gage in inches												Mean
	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	Met. R	
1938													
Oct.	0.70*	0.54	0.73*	0.70*	0.62	0.62	0.56	0.73*	0.69*	0.72*	-----	0.61	0.66
Nov.	3.52*	2.95	-----	-----	3.05	-----	-----	3.27	3.17	3.81*	3.45*	2.93	3.27
Dec.	1.45	1.34	1.62*	1.85*	1.31	-----	-----	1.51*	1.38	1.50*	1.47	1.27	1.47
1939													
Jan.	2.74*	2.36	-----	-----	2.11	-----	-----	2.56*	2.40*	-----	2.55*	2.04	2.39
Feb.	4.91*	4.17	-----	-----	4.21	-----	-----	4.78	5.36*	6.39*	4.70	3.99	4.81
Mar.	3.82*	3.79*	3.94*	3.87*	3.60	-----	-----	3.87*	3.52	3.69	3.71	3.59	3.74
Apr.	4.22*	3.83	4.16*	3.96	3.85	4.20*	4.11*	4.21*	3.94	4.10*	4.00	3.75	4.03
May	1.63*	1.51	1.65*	1.59*	1.52	1.57*	1.55	1.59*	1.57*	1.57*	1.58	1.39	1.56
June	7.13*	6.94	7.02	6.87	7.12*	7.10*	7.06*	7.15*	7.02	7.08*	7.02	6.85	7.03
July	6.98	6.83	7.16*	6.95	6.90	7.40*	7.38*	7.25*	6.96	7.14*	6.97	6.84	7.06
Aug.	1.39*	1.35	1.36*	1.37*	1.32	1.29	1.29	1.42*	1.37*	1.36*	1.37*	1.28	1.35
Sep.	1.16*	1.12	1.18*	1.16*	1.13	1.13	1.15*	1.14	1.14	1.16*	1.17*	1.07	1.14
Oct.	4.62*	4.38	4.74*	4.55	4.53	4.58*	4.59*	4.70*	4.54	4.57	4.54	4.48	4.57
Nov.	0.64	0.59	0.69*	0.64	0.62	0.64	0.64	0.66*	0.65*	0.68*	0.65*	0.57	0.64
Dec.	R	1.67	R	R	1.49	R	R	1.69	1.68	-----	1.78	1.73	-----

* = Catch for gage exceeded mean catch of all gages for month. R = Gage removed.

Regression of catch for certain selected gages was computed against gage MB and includes all storms exceeding 0.02 inch except hail or snowstorms. In computing the regression-equations for gages ME, MH, MI, MJ, MK, and Met. R the entire period of record for each gage was used regardless of the fact that these periods are not of equal length. Regression-factors are listed in Table 7.

Tables 1 to 7, as previously described, furnish a basis for a general comparison of the various gages which are described and discussed in the following paragraphs:

MA--A standard gage and tripod are placed in the center of a square plot that is 24 feet on

Table 3--Precipitation for storms exceeding 0.75-inch total as measured at gages having various types of shields and enclosures, 1937

Date	Catch of each gage in inches												Mean
	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	Met. R	
Jan. 12-14	2.55*	2.42	----	----	2.45*	----	----	----	----	----	----	2.31	2.43
17-18	1.13*	1.07*	----	----	1.06*	----	----	----	----	----	----	0.98	1.06
19-20	1.22*	1.20*	----	----	1.20*	----	----	----	----	----	----	1.12	1.18
21	1.57*	1.55*	----	----	1.54	----	----	----	----	----	----	1.48	1.54
24	2.16*	1.96	----	----	1.98	----	----	----	----	----	----	1.95	2.01
Apr. 14-15	1.30*	1.27	----	----	1.25	1.33*	1.28	1.40*	----	----	----	1.21	1.29
May 14	0.82	0.78	----	----	0.79	0.91*	0.87*	0.87*	----	----	----	0.77	0.83
27	0.81	0.78	----	----	0.78	0.94*	0.94*	0.88*	----	----	----	0.81	0.85
June 6	0.88	0.82	1.13*	1.93*	0.88	0.94	0.90	0.91	----	----	----	0.80	1.02
9-10	1.04	1.02	1.08*	1.05	1.02	1.08*	1.03	1.11*	----	----	----	1.02	1.05
14	1.31	1.24	2.00*	1.80*	1.33	1.95*	1.93*	1.40	----	----	----	1.20	1.57
20-21	2.56	2.58	2.80*	2.64	2.54	2.70*	2.64	2.78*	----	----	----	2.60	2.65
21	1.02	1.00	1.17*	1.13*	1.00	1.02	1.00	1.11*	----	----	----	0.93	1.04
July 5	0.88	0.90	1.04*	0.98*	0.93	1.04*	1.00*	0.93	----	----	----	0.86	0.95
14	1.07	1.04	1.05	1.11*	1.07	1.09*	1.07	1.11*	----	----	----	0.99	1.07
16-17	2.56	2.48	3.20*	2.94*	2.62	3.18*	2.98*	2.60	----	----	----	2.68	2.80
Aug. 10	1.06	1.07	1.13*	1.10	1.15*	1.07	1.03	1.23*	----	----	----	1.07	1.10
26	0.84*	0.80	0.85*	0.81	0.81	0.80	0.81	0.90*	----	----	----	0.82	0.83
Oct. 5	0.88*	0.88*	0.90*	0.86	0.85	0.88*	0.86	0.90*	----	----	----	0.85	0.87
18	1.36	1.32	1.39*	1.18	1.28	1.64*	1.52*	1.32	----	----	----	1.28	1.36
Dec. 16-18	2.42*	2.40	2.43*	----	2.39	----	----	2.45*	----	----	----	2.33	2.40

* = Catch of gage exceeded mean catch of all gages for storm.

Table 4--Precipitation for storms exceeding 0.75-inch total as measured by gages having various types of shields and enclosures, 1938

Date	Catch of each gage in inches												Mean
	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	Met. R	
Feb. 18-20	0.98*	0.85	----	----	0.86	----	----	0.90	0.97*	----	----	0.82	0.90
Mar. 5	0.78	0.75	0.80*	0.81*	0.77	0.82*	0.79*	0.81*	0.77	----	----	0.73	0.78
13-14	2.12	2.05	2.15*	2.19*	2.05	2.27*	2.07	2.22*	2.06	----	----	2.00	2.12
15-16	0.75	0.76	0.78*	0.75	0.75	0.78*	0.74	0.77*	0.74	----	----	0.75	0.76
22	0.80	0.96	0.92	1.05*	1.11*	0.97	1.12*	1.07*	0.94	----	----	0.97	0.99
Apr. 6	----	1.86*	1.92*	1.87*	1.85	1.80	1.75	1.87*	1.85	----	----	1.85	1.85
May 8	----	0.80	0.96*	0.92	0.90	0.97*	0.98	0.88	0.88	0.99*	----	0.88	0.92
14-15	----	1.58	1.69*	1.60	1.60	1.75*	1.64	1.65*	1.59	1.65*	----	1.60	1.64
17-18	----	0.89*	0.91*	0.90*	0.88	0.88	0.85	0.90*	0.87	0.90*	----	0.85	0.88
June 11	1.02	1.00	1.11*	1.02	0.98	1.16*	1.10*	1.05	1.03	1.10*	----	1.02	1.05
16	0.85	0.88	0.92*	0.84	0.85	0.97*	0.96*	0.97*	0.86	0.85	----	0.85	0.89
26	0.85*	0.82	0.87*	0.80	0.80	0.87*	0.84	0.87*	0.83	0.86*	----	0.82	0.84
July 17-18	0.83*	0.78	0.81*	0.79	0.80*	0.77	0.77	0.81*	0.80*	0.81*	----	0.77	0.79
July 31-Aug. 1	2.05*	1.93	1.98	2.00	1.98	2.06*	2.05*	2.04*	1.95	2.00	----	1.99	2.00
Aug. 4	1.43	1.44	1.56*	1.48	1.45	1.69*	1.65*	1.57*	1.53	1.60*	----	1.50	1.54
10-11	0.53	0.53	0.55	0.55	0.56*	0.58*	0.57*	0.55	0.53	0.57*	----	0.53	0.55
Sep. 13	0.80*	0.73	0.83*	0.75	0.74	0.85*	0.82*	0.76	0.75	0.84*	----	0.72	0.78

* = Catch of gage exceeded mean catch of all gages for storm.

each side. A tight board-fence, four feet high, is constructed on the sides of the plot. The fence serves to break up lateral drift, at the same time maintaining uniform air-turbulence over the gage. Its snow-catch (Table 6) was high among the shielded gages, but did not show extreme values due to drift-action as was the case for gages located in pit-type enclosures. The effect of the enclosure was quite erratic for the larger rainstorms (Tables 3 to 5). The space required by the large enclosure and the cost of installation and maintenance of the tight board-fence make its use practically prohibitive for a large number of units.

Table 5--Precipitation for storms exceeding 0.75-inch total as measured by gages having various types of shields and enclosures, 1939

Date	Catch of each gage in inches												Mean
	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	Met. R	
Jan. 30	1.44	1.37	1.94*a	2.42*a	1.30	----	----	1.42	1.34	1.41	1.42	1.31	1.54
Feb. 15b	1.54	1.30	2.70*	4.54*	1.35	----	----	1.45	1.32	2.25*	1.45	1.28	1.92
Mar. 12	1.70*	1.62	1.77*	1.72*	1.62	----	----	1.75*	1.55	1.68*	1.65	1.58	1.66
30	0.90*	0.96*	0.89*	0.86	0.85	0.95*	0.93	0.86	0.86	0.86	0.85	0.85	0.88
Apr. 6	0.73*	0.69	0.72	0.71	0.70	0.75*	0.72	0.72	0.71	0.73*	0.73*	0.68	0.72
18	1.13*	1.07	1.13*	1.11	1.10	1.08	1.11	1.22*	1.10	1.12*	1.13*	1.08	1.11
June 11	0.88*	0.86	0.89*	0.88*	0.84	0.90*	0.91*	0.89*	0.85	0.89*	0.87	0.84	0.87
13	0.93	0.93	0.93	0.90	0.94*	0.93	0.95*	0.95*	0.90	0.95*	0.94*	0.92	0.93
19	3.16*	3.08	3.08	3.00	3.28*	3.30*	3.22*	3.15*	3.15*	3.12	3.11	3.07	3.14
July 4	0.75	0.74	0.77	0.76	0.76	0.80*	0.82*	0.75	0.75	0.75	0.76	0.82*	0.77
8	1.65	1.61	1.70*	1.64	1.60	1.85*	1.82*	1.66	1.63	1.73*	1.62	1.64	1.68
8	0.86	0.85	0.90	0.85	0.87	1.04*	1.02*	0.85	0.88	0.92*	0.88	0.84	0.90
20	0.88	0.88	0.91*	0.88	0.88	0.90	0.92*	0.99*	0.90	0.88	0.88	0.86	0.90
Sep. 30	0.69*	0.67	0.69*	0.66	0.66	0.70*	0.71*	0.69*	0.68	0.70*	0.69*	0.63	0.68
Oct. 25	2.68*	2.59	2.72*	2.59	2.62	2.61	2.59	2.74*	2.64	2.64	2.64	2.64	2.64
27	1.52*	1.38	1.56*	1.56*	1.49	1.55*	1.53*	1.56	1.46	1.51*	1.49	1.46	1.50

* = Catch of gage exceeded mean catch of all gages for storm. a = Snow washed in. b = Snowstorm.

Table 6--Catch by experimental gages during snowstorms, 1938 and 1939

Date	Catch of snow in equivalent inches of water											
	MA	MB	MC	MD	ME	MF	MG	MH	MI	MJ	MK	Met. R
1938												
Nov. 23	0.12	0.04	0.15	0.16	0.03	----	----	0.07	0.05	0.09	0.07	0.03
25	0.43	0.23	2.00 b	1.54 b	0.15	----	----	0.19	0.23	0.45	0.23	0.11
28	0.04	0.03	2.50 b	2.30 b	0.03	----	----	0.04	0.03	0.29	0.06	0.03
Dec. 24	0.15	0.14	0.23	0.29	0.12	----	----	0.18	0.15	0.18	0.18	0.13
30	0.03	0.01	0.04	0.22	0.01	----	----	0.02	0.01	0.02	0.02	0.01
1939												
Jan. 15	0.50	0.40	3.61 b	1.97 b	0.25	----	----	0.39	0.39	1.48b	0.37	0.22
16	0.10	0.08	0.17	0.08	0.08	----	----	0.09	0.08	0.09	0.09	0.09
19	0.19	0.14	0.25	0.82 b	0.12	----	----	0.18	0.17	0.20	0.17	0.10
21	0.02	0.04	0.04	0.02	0.02	----	----	0.02	0.03	0.03	0.02	0.04
25	0.06	0.01	0.68 b	0.50 b	T	----	----	0.03	0.03	0.24b	0.03	0.01
27	0.18	0.11	1.40 b	1.36 b	0.10	----	----	0.17	0.15	0.40b	0.17	0.08
Feb. 3	0.31	0.21	1.16 b	2.98 b	0.19	----	----	0.24	0.23	0.67b	0.29	0.17
15	1.54	1.30	2.70 b	4.54 b	1.35	----	----	1.45	1.32	2.25b	1.45	1.28
21	0.45	0.30	a	a	0.30	----	----	0.34	a	0.31	0.42	0.22
23	0.06	0.01	a	a	0.01	----	----	0.02	0.02	0.45	0.03	0.01
Apr. 12	0.10	0.08	0.09	0.10	0.02	----	----	T	0.04	0.06	0.04	0.04
Dec. 20	c	0.14	c	c	0.09	----	----	0.10	0.11	0.18	0.13	0.05
28	c	0.21	c	c	0.12	----	----	0.20	0.19	0.58	0.19	0.08
31	c	0.01	c	c	0.01	----	----	0.04	0.03	a	0.04	0.37
Total	d	3.49	d	d	3.00	----	----	3.77	3.28e	7.97	4.00	3.07

a = Not read. b = Snow drifted into gage. c = Gage removed. d = Total not listed due to incomplete record. e = Note that this total contains no correction for missing record of February 21, 1939.

MB--This is the type of standard field-installation used by the Hydrologic Division for the determination of precipitation upon a watershed-basis. It consists of a standard Weather Bureau type non-recording gage placed in a metal tripod and surrounded by a woven-wire enclosure. The woven-wire enclosure is quare, eight feet on a side, and consists of hog wire with the top strand four feet above the ground. This gage was consistently low in catch by storms and by months both for rain and snow. Its catch for storms was frequently more than ten per cent below the

Table 7--Statistical comparison of various experimental gages with gage MB

Item	ME	MB	MI	MJ	MK	Met. R
Regression-coefficient[a]	1.01	1.032	1.026	1.036	1.030	1.001
Mean catch[b]	MB=.399 ME=.403	MB=.407 MH=.412	MB=.402 MI=.422	MB=.420 MJ=.444	MB=.439 MK=.454	MB=.409 Met. R=.406
Standard deviation[c]	.525	.510	.524	.519	.537	.494
Standard error of estimate[d]	.082	.084	.169	.038	.024	.051
Per cent of standard deviation due to experimental error[e]	12	16.4	32.2	7.35	4.5	10.1

[a] The regression-coefficient is the average increase in catch of the given experimental gage for each unit-increase in catch of gage MB.

[b] The mean catch is the arithmetic average of all measured rains, excluding snowstorms and rains of less than 0.02 inch, during the entire period of record.

[c] The standard deviation is expressed by the formula, $\sqrt{Sd^2/(n-1)}$, where d is deviation of each measured rain from the mean and n is the number of measured rains.

[d] Standard error of estimate is an average of the differences between measured rains in the given experimental gage and catch as computed by applying the regression-equation to the catch of gage MB.

[e] The standard error of estimate divided by the standard deviation, times 100, gives the per cent of deviation from mean due to causes other than regression of one gage upon the other.

catch of the shielded gages. On a monthly basis it was in no case higher than fourth in rank. The need for protection from wind-action is clearly indicated.

MC--A masonry-lined pit, four feet in diameter and three feet deep, serves as the enclosure for a standard non-recording gage in a metal tripod. When the receiver of the gage is in place, its top is at the center of the pit and flush with the surface of the ground. This gage exceeds all the others in ability to maintain first or second place in rank as based on amount of catch by storms or months. This high catch is due in part to the protection from wind-action as afforded the gage by the pit, this being a desirable feature. Another large part of the increase results from "drifting" rain carried along the surface of the ground by strong wind and deposited in the gage-receiver. This undesirable action is due to the small diameter of the pit. It is difficult to maintain a cover of turf over the top of the masonry-wall of the pit. When the top of this wall was uncovered, splash may have carried from it into the gage-receiver. The catch of this gage during snowstorms (Table 3) was undependable due to drifts forming in the pit. For the above reasons and also due to cost of constructing and maintaining the pit this type of enclosure does not appear to be worthy of further study.

MD--The enclosure for this gage consists of a pit four feet by five feet in surface-area and three feet deep. The gage is placed at the center of the pit with the top of the receiver flush with the ground-surface. The opening which surrounds the receiver is covered with a cocoa-brush mat to simulate natural sod and to prevent the splash which would occur with a tight and hard cover of lumber or metal. A narrow opening is left between the edge of the mat and the circumference of the receiver to facilitate drainage of water which may accumulate on the surface of the mat. Measurements by this gage were erratic throughout the period of observation. For snowstorms its catch was invariably high due to the rapid deposit of drifting snow in the eddy formed by the gage-receiver. Rainstorms of high intensity accompanied by strong wind produced the same action. At other times air-currents passing over the cocoa mat seemed to deflect rain from the gage-receiver. Because of these results and the excessive cost of installation and maintenance this gage is eliminated from further consideration in this study.

ME--This standard non-recording rain-and-snow gage, without shield, fence, or enclosure, is similar to gage MB (standard-wire enclosure) in its function, since the only difference between the two is the open woven-wire fence surrounding MB. Results from the two gages are quite similar although not identical.

MF--This is a standard non-recording rain-gage in a metal tripod and without enclosure. The receiver contains a multiple-vane-type shield as developed by Hall [2] of the Los Angeles County

Flood Control District. The object of the vanes is to present an approximately uniform catchment area to precipitation carried by strong winds.

MG--This gage is identical with MF with the exception of slots which have been cut in the vertical receiver-vanes with the purpose of reducing the buffer-action inherent to the vertical vanes.

Results from the above two gages are similar, although gage MG with the slotted vanes usually records slightly less precipitation than gage MF. In monthly catch these gages exceed MB and ME in yearly every instance. For storms exceeding 0.75 inch their catch is frequently ten per cent or more in excess of MB and ME. The vane-type shields quickly pack full of snow and are therefore not adapted to winter use. While these snields do show a higher catch than the unprotected gages it is noted that their catch is not consistent with that of Nipher shielded gages MH and MK, with gage MI, or with gage MJ in the large pit. This inconsistency raises serious question as to the efficacy of the Hall shields. For these reasons this type of shield is eliminated from furtner consideration in the study.

MI (see Fig. 1)--The standard non-recording rain-gage is equipped with a snow-fence snield. This shield consists of wooden lath placed radially upon the surface of an inverted truncated cone with the upper ends of the lath about one inch apart and flush with the top of the receiver of the gage. This shield has the same general objective as the Nipher shield. This study indicates that the snow-fence shield may be built and installed economically and that it requires little maintenance. Its effect as a wind-snield on precipitation-gages is apparent although not so pronounced as the Nipher shield. Out of 23 months of record the catch of this gage exceeded the mean of all gages only seven times. Its action as a shield for snowfall (Table 6) was more satisfactory than for rainfall. Its regression-coefficient of 1.026 is low as compared with the Nipher snields and the large pit. The standard error of estimate at 0.169 is high.

MJ (see Fig. 2)--In this installation the standard non-recording rain-gage is placed within a circular masonry-wall. This wall is built up one foot above the ground-surface and has an inside diameter of ten feet. The receiver of the rain-gage is placed in the center of the ten-foot circle with the top of the receiver flush with the top of the wall. The top of the wall is six inches wide and from the outside edge an earth-fill slopes downward on a 1:4 slope until it intersects the natural ground-surface. The fill is covered with turf. The inner part of the masonry-wall slopes down from the top of the wall to the bottom of the tripod four feet below the top of the gage-receiver. This inner conical surface of the pit is lined with broken stone. This gage proved to be a distinct improvement over the small pit as first constructed for gage MC. Due to the larger pit opening there is much less opportunity for rain to drift into the gage-receiver. The recorded measurements plus observations of the gage in action lead to the conclusion that it catches an accurate sample of ground-rainfall. The catch by the gage during snowstorms is undependable due to formations of drift within the pit. For this reason and because of high cost of construction and maintenance it is eliminated from further consideration in this study. However, it is believed that its use should be given consideration in regions not subject to considerable snowfall. Its regression-coefficient of 1.036 was the highest of all the experimental gages and the standard error of estimate at 0.038 is low. For the 18 months of record there are only two in which catch by this gage did not exceed the mean catch by all gages.

MH--In this case the standard non-recording rain-gage is equipped with an adaptation of the Nipher [3] shield. There is no enclosure around the gage. The object of the snield is to convert cross-currents and updrafts into reverse eddy-flows that will create a turbulent but relatively calm region above the gage-receiver.

MK (see Fig. 3)--The standard non-recording rain-and-snow gage is equipped with the Nipher shield as used by Dr. Charles F. Brooks at the Blue Hill Observatory [4]. There is no enclosure about the gage. The effect of these Nipher shields in protecting the precipitation-gage from wind-action during both rainfall and snowfall has been more satisfactory than that of any of the other shields or enclosures. The cost of installing standardized and simplified shields on a large number of gages is not excessive and cost of maintenance is low. The catch of these gages by storms and months was consistently higher than that of the unshielded gages, but did not reach the extreme values of the various pit-gages. Their action was equally consistent for rainstorms and snowstorms. The snield used on gage MK is the improved Nipher developed by Dr. Brooks and is superior in action to MH which is the first adaptation of the Nipher as tried at Coshocton. The screen over the top surface of shield MK prevents splash and the large annular opening between the snield and the outside of the gage prevents piling up of snow. The regression-coefficients of the two Nipher shielded gages at 1.032 for MH and 1.030 for MK are nearly identical. The standard error of estimate at 0.084 for MH and 0.024 for MK reflects the improvement in shield

Fig. 1

Fig. 3

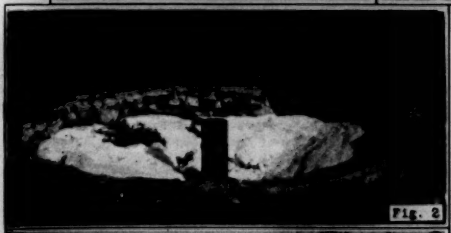


Fig. 2

Fig. 5

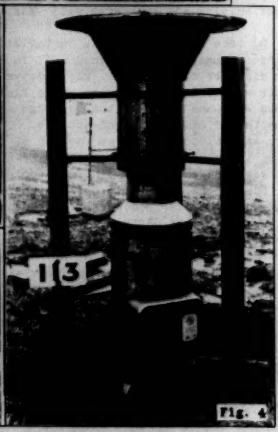
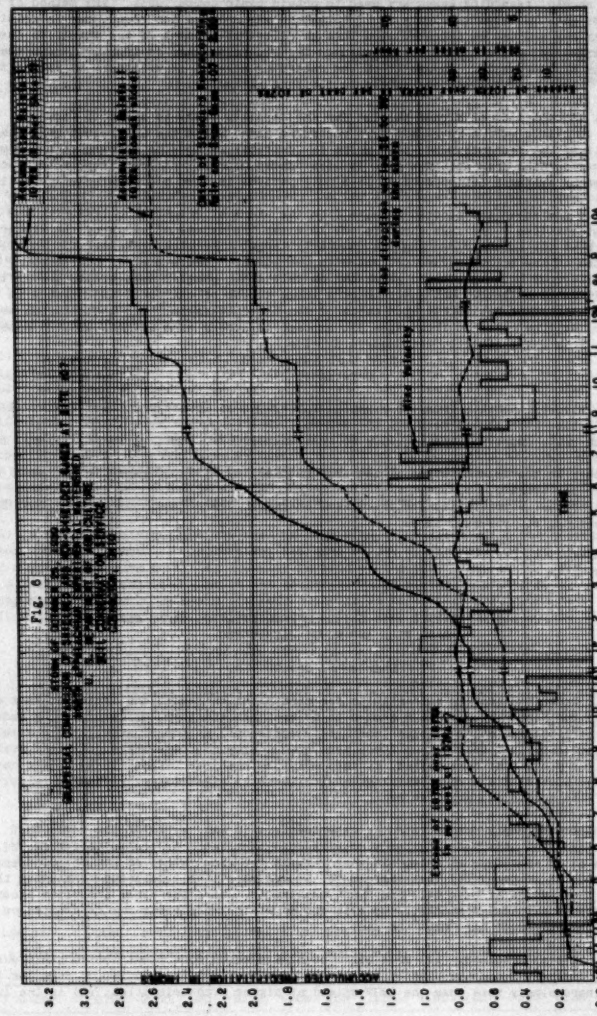


Fig. 4

Fig. 1--Snow-fence shield installed on standard rain-and-snow gage MI
Fig. 2--Standard non-recording rain-and-snow gage MJ located in large pit-type enclosure
Fig. 3--Improved Nipher shield installed on standard non-recording rain-and-snow gage MK
Fig. 4--Trial installation of Nipher shield on Fergusson recording rain-and-snow gage
Fig. 5--Typical field-installation for study of effect of Nipher shield consists of Fergusson recording rain-and-snow gage with Nipher shield, reconnaissance recording rain-and-snow gage without shield, standard non-recording rain-and-snow gage, and recording anemometer

MK. On the basis of these exploratory studies it appears that the Nipher shields possess most of the characteristics required of a shield for application to rain-gages located in the watershed-studies. The Nipher shield is now being subjected to a more intense study to determine its actual effect upon catch of precipitation under various conditions of exposure, wind-velocity, and rain-intensity.

Met. R--Judging from data collected in this study, and further verified by numerous paired field-installations of Fergusson type recording-gage and standard non-recording gage, it appears that the recording gage is more in need of shielding than is the standard non-recording gage. Both for storms and months, for either rainfall or snowfall, the recording gage was among the



lowest in rank of all the gages. It is believed that this low catch is due to the sloping shoulders on the recording gage which cause updrafts.

In the study which is now under way to determine the fundamental reasons for effectiveness of the Nipher shield, recording gages are used to obtain basic comparisons. The method of attachment to the gage is shown in Figure 4. This method was adopted for expediency in getting the study under way and can be improved upon through direct attachment of the shield to the top portion of the recording gage. The shield used on the recording gage is identical with that developed for the standard gage. To use it on the recording gage it is necessary to extend the receiver by a "stack" and elevate the shield to fit this extension.

A typical installation of Nipher shields for the detailed study is shown in Figure 5. The Nipher shield is placed over a Fergusson type recording-gage, while the unshielded gage placed 12 feet away is of the reconnaissance type which is identical in outside appearance and dimension. A standard non-recording rain-and-snow gage is also placed nearby. An anemometer which records wind-velocities by averages for successive 15-minute periods is also placed within the enclosure.

In Figure 6 are shown the plotted results from the storm of October 25, 1939, for one of these test-installations. The case shown is one in which the excess of catch by the Nipher shielded gage over the non-shielded gage is unusually large. The recorder-chart is, in all cases, corrected to the actual volume collected in the bucket. There are, of course, many storms in which no difference between the two gages can be detected. Usually such storms are of low wind-activity. It is believed that analysis of a large number of charts of this type will evaluate the effect of wind-velocity upon catch of non-shielded gages. The most dependable results, however, will be obtained from gages not exposed to strong wind-action, and, in case of such exposure, from gages equipped with modern shields.

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FURTHER EXPERIENCE WITH SHIELDED PRECIPITATION-GAGES ON BLUE HILL AND MOUNT WASHINGTON

Charles F. Brooks

In 1938, I described certain wind-shields for precipitation-gages, and indicated that a design closest to the Nipher type of 1878 seemed to be most satisfactory, allowance being made, however, for the discharge of snow below [see 1 of "References" at end of paper]. Since this "best" design had only just been set up there were practically no comparative data then available. In the two years that have passed, catches obtained with the latest (1838) shield have been compared on Blue Hill and Mount Washington with those in gages carrying other shields, and, on Blue Hill, with unshielded gages as well.

Since it has been amply demonstrated by experimenters in many parts of the world that precipitation-gages not shielded from the wind give deficient catch of precipitation [2, 3], the problem now is as to what type of shield is best. While the experiments of the Soil Conservation Service at Coshocton on generally flat terrain [4, 5] are more likely to prove conclusive than those made on the summits of Blue Hill and Mount Washington, where the winds are often excessive and have a variable vertical component, the hill and mountain experiments may be counted on to show certain limitations of our "best" shield.

There are several problems: (1) Does our 1938 shield catch more precipitation than our 1937 shield (having a single slope and blunter, 35° angle of attack for the wind); (2) does our 1938 shield catch increasingly more than the 1937 shield at higher wind-velocities; (3) is the 1938

Table 1--Precipitation-catches of gages in 1938 and 1937, wind-shields exposed at a height of five or six feet above the rocks on the southwest side of the summit of Mt. Washington, where the surface slopes 4° to 6° to the west, the gages and their shields being tilted at this angle to the west to present their orifices parallel to the average air-stream. June 1, 1938, to Feb. 3, 1939

Item	1938 shield	1937 shield	1938/1937
	Inches	Inches	Per cent
(a) Catches of rain or of rain and snow within the same 6-hour period	45.35	44.09	103
(b) Catches of snow alone	21.26	20.39	104
(c) Total precipitation caught	66.61	64.48	103

shield effective even at high wind-velocities; and (4) is fine wire-screening necessary to reduce splash from the shield?

(1) Does our 1938 shield catch more precipitation than the 1937 shield?--A 1938 shield was installed beside a 1937 shield on the southwest side of the summit of Mount Washington in May, 1938, and left there till February, 1939, when it was moved to the north slope of the summit. Tables 1 and 2 show the catches of the two gages included in these shields. The answer is, thus, "Yes, but only three to seven per cent more, part of which is probably splash and drift from the flat rim of the shield."

(2) Does our 1938 shield catch increasingly more than the 1937 shield at higher wind-velocities?--Table 2 presents the snow-catches grouped according to the wind-velocity. Only northwest, west, and southwest winds have been considered, because winds from other directions have to pass over buildings first, and thereby produce anomalous differences apparently in actual precipitation at points only a few feet apart which tend to obscure the true effect of the shields. Table 2 shows a lesser advantage of the new shield (No. 9) over the old one (No. 8) at low velocities (seven per cent) than at medium velocities (15 per cent), as would be expected; but the advantage decreases to nine per cent at the higher velocities, and becomes zero for winds in excess of 75 miles per hour. The sample, however, may not be adequate. The new shielded gage caught 20 per cent more of drifting snow, namely, 5.04 inches against 4.20 inches.

(3) Is the 1938 shield effective even at high wind-velocities?--With the catches of both the newer and the older shield approaching the same values in excessive winds, it looks as if neither might be catching more than a small fraction of the snowfall. In the snowstorm of April 21-22, a 1938 type of shielded gage on the southeast slope of the summit of Mount Washington, fully exposed to a wind of (minimum six-hour velocity)72 mi/hr to (maximum one-hour velocity)89 mi/hr from the east changing to northeast, caught 0.72 inch of precipitation (and drift) and

Table 2--Snow-catches on the summit of Mt. Washington, northwest of the Observatory, October 1, 1938, to February 3, 1939

[All precipitations that in a period of measurement included both rain and snow have been omitted; only the falls with westerly (northwest, west, southwest) winds have been included, to avoid turbulent effects of the buildings; the values are the water derived from melting the snow-catches; No. 8 is the shield of 1937; No. 9 is the shield of 1938 (with nearly flat outer rim)]

Mean wind-velocity in 6-hour period	Prevailing wind-direction during the 6-hour period of each catch											
	Northwest			West			Southwest			Northwest, west, southwest		
	No.8	No.9	9/8	No.8	No.9	9/8	No.8	No.9	9/8	No.8	No.9	9/8
mi/hr	inch	inch	per cent	inch	inch	per cent	inch	inch	per cent	inch	inch	per cent
0- 25	0.22	0.25	114	0	0	---	0.18	0.18	100	0.40	0.43	107
26- 50	0.51	0.61	119	1.35	1.54	114	0.44	0.50	114	2.30	2.65	115
51- 75	0.95	0.92	97	0.55	0.56	102	0.63	0.81	129	2.13	2.33	109
76-100	0.88	0.78	88	1.85	1.98	107	0.16	0.13	81	2.89	2.89	100
0-100	2.56	2.56	100	3.75	4.08	109	1.41	1.62	115	7.72	8.30	107

Table 3--Percentage-increase of catch owing to splash when wire netting was removed from wind-shield No. 9, summit of Mt. Washington (negative values indicate decrease)

Type of rain	Wind-velocity, miles/hour			
	0-25	26-50	51-75	0-75
Heavy	-1	5	-5	3
Light-moderate	8	2	2	2
Light-heavy	3	5	2	3

Table 4--Percentage-increase of relative catch of a gage at two feet owing to splash when wire netting was removed from inner surface of the 56-inch Nipher shield about it, Blue Hill

Type of rain	Wind-force (Beaufort)	
	1-4	5-8
Heavy	5	6
Light-moderate	1	3
Light-heavy	3	4

another like it on the north slope caught 0.46 inch, whereas the 1937 shield on the west slope caught 1.78 inches, and 1.11 inches fell at Hermit Lake, Tuckerman Ravine (partly drift). In the windy snowstorm of February 14-15, 1940, on Blue Hill, with a wind up to (maximum hour) 51 mi/hr and even (five minutes) 70 mi/hr and (one (?) second) 80 mi/hr, the 1938 shielded-gage (shield about a Fergusson weighing recording-gage) five feet above the ground retained only 0.26 inch out of 2.76 inches of precipitation (as measured by cutting sections from the cover at the base of the hill). Whether an unshielded gage at the same or any height would have retained any more is not known. That on the ground tipped over. The Nipher shielded-gage two feet above the ground caught 1.94 inches of snow and drift. Deeper cans or eddy-reducing vanes in them seem indicated.

(4) Is fine wire-screening necessary to reduce splash from the shield entering the gage?--On Mount Washington when the 1938 shielded-gage was installed near the 1937 gage the wire-screening on the new gage was on and off alternate months during the summer of 1938. Table 3 shows the difference. The 1938 shielded-gage caught three per cent more when the screening was off, apparently owing to splash, which was slightly greater in heavy rains than in light, though perhaps not as much as would be expected.

Table 4 gives roughly corresponding data for Blue Hill. One gage was at two feet and surrounded by a Nipher shield 56 inches in diameter; the other was at six feet and surrounded by a 1938 type of Nipher shield. The low gage had the usual Weather Bureau funnel and small tube and had fine wire-netting one-fourth inch above the entire inner surface of its shield from July to October, 1938, and from May to October, 1939. It was without funnel, tube, and screening from November, 1938, to April, 1939. The shielded gage at six feet had no funnel or tube and no screening at any time. The effect of the funnel and tube in the warmer seasons is to reduce the evaporation and thereby increase the relative catch measured relative to a gage not so equipped. This would tend to diminish the apparent splash-reducing effect of the screening. In other words, the values in Table 4 are less than the true splash-difference by the small amount of evaporation from an open rain-gage can in contrast to a nearly closed one. A heavy rain is taken as 0.51 inch or more in 12 hours.

The gage without screening and without the funnel and tube caught and retained five per cent more in heavy rains and one per cent more in light to moderate rains than the gage with screened shield and funnel in winds of Beaufort 1 to 4, over a period of six months, May to October, 1939, with 11.5 inches of rainfall. The summers of 1938 and 1939, however, each showed the same average excess of three per cent, though both shields were screened in 1938. From November, 1939, to April, 1940, the catch of a Fergusson recording-gage surrounded by a bare shield of 1938 type was compared with that of the open gage at two feet in a fully screen-covered Nipher shield 56 inches in diameter, with similar, though less significant, results, for the rain that fell during light to moderate winds was only 1.93 inches. The excess catch of the gage in the unscreened shield was nine per cent. These comparisons seem to indicate that fine wire-screening is necessary to reduce splash from the Nipher type of wind-shield about a rain-gage. Indeed, it should hardly be called a Nipher type of shield unless it carries screening, for Professor Nipher's shield of 1878 provided in just this way against splash.

Conclusion--After a considerable amount of experimenting with cheaper substitutes for Nipher's design, we must return to it. The outer horizontal or nearly horizontal rim to divert the wind downward more effectively increases the catch, especially in moderately strong winds, over a shield without such a rim. In strong gales, however, it seems to make little difference, so great is the general turbulence. The screening that Professor Nipher specified for the inside

of the shield is also found to be necessary, for without it the splash apparently augments the rain-catch by some three per cent. Nipher shields (without screening) of the 1938 type used in the Blue Hill and Mount Washington experiments, except that the outer rim is horizontal instead of sloping 10°, are now manufactured by M. C. Stewart, Arlington, Massachusetts.

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PREDICTING HEADWATER RIVER-STAGES DIRECTLY FROM RAINFALL

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Flood-forecasters have frequently made use of tabulations showing the crest-rise in feet per inch of rainfall for large storms on particular headwater drainage-basins. Values of crest-rise per inch of rainfall might well be termed unit-crests and, as would be expected, they vary widely for different storms. The value of unit-crest to be used in forecasting for a particular storm would be based on a previous storm of similar characteristics and accompanying soil-conditions.

The purpose of this paper is to demonstrate that with the use of refinements, such as initial loss, an index of soil-condition, and an adjustment for duration of rainfall, values of crest-rise can be satisfactorily correlated with rainfall. The principal reason for using such a procedure rather than one of the more refined methods involving rainfall-runoff relations, unit-hydrographs, etc., is the saving of time in making predictions.

To gain as great a time advantage as possible, a forecaster usually must make crest-predictions from rainfall for a number of headwater-basins and then route the results downstream to make forecasts for larger areas. Of minor importance is the fact that relations can be developed for river-stations where stage-readings, but no discharge-measurements, are available.

The use of a drainage-basin "lag", the underlying conception of rainfall-runoff relations, and the mechanics of analysis are practically the same as those set forth in two previous papers [see 1, 2 of "References" at end of paper].

The present procedure has usually been applied to drainage-areas of 1,000 square miles or more. For illustration a small watershed with numerous rain-gages was selected, namely, the West Fork River above Weston, West Virginia. The drainage-area is 123 square miles and published records are available for six rain-gages. The river-gage is not an automatic recorder but is read regularly once a day and more frequently during floods; so that the crest-stages are available for most of the rises during the last several years.

The West Fork River has its source in the southwestern part of Upshur County, West Virginia, at an elevation of about 1,700 feet. The River drops 50 feet in the 15 miles above Weston to an elevation of about 1,000 feet at Weston. The hilltops range from elevations of 1,500 to 1,900 feet. Sections of the main valleys have considerable bottom-land through which the streams meander. The length of the basin above Weston is about 17 miles, while the length of the principal channel is about 30 miles.

Table 1 gives the base-data for the storms analyzed. Column (c) gives the index ground-water stage at the gaging station "T" days after the beginning of surface-runoff (but on the same depletion assuming no rise) where T is the duration of the unit-hydrograph for the basin (c, Fig. 1). The base-stage, column (d), is the stage which would have existed at the time of cresting if the rise under analysis had not occurred (d, Fig. 1).

Column (f) is the crest-rise for the storm and is obtained by subtracting the base-stage from the crest-stage.

Column (g) gives the basin-precipitation obtained by averaging the amounts measured at six well-distributed stations (Ireland, Crawford, Roanoke, Vandalia, Brownsville, and Weston, West

Table 1--Storm-data for West Fork River above Weston, West Virginia (drainage-area, 123 square miles)

Storm No.	Date	Index ground-water	Base	Crest	Crest-rise, feet	Precip-itation, inches	$(P-L_1)$, inches	Unit crest-rise, feet per inch	Final ground-water stage, feet	Duration of precip-itation (t_R), hours	Ob-served lag, hours	Lag (t_{pR}), hours	Lag (t_p), hours	Ad-justed crest-rise, feet
		Stage, feet												
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(m)	(n)	(o)	(p)
1	Oct. 2, 1929	-0.2	0.0	18.0	18.0	3.68	3.62	5.0	1.1	28 M	18	18	12	27.0
2	June 21, 1937	0.0	0.2	17.0	16.8	2.89	2.66	6.3	0.6	3 M,U	13	12	12	16.8
3	Oct. 27, 1937	0.3	0.6	17.6	17.0	3.81	3.73	4.6	1.2	44 M	21	21	11	29.8
4	May 15, 1938	-0.25	-0.2	3.3	3.5	1.90	1.54	2.3	0.1	26 M	29	29	(23)	8.5
5	May 18, 1938	-0.1	0.4	3.3	2.9	0.68	0.59	4.9	0.2	10 M	22	22	(20)	5.3
6	May 19, 1938	0.0	1.8	14.2	12.4	1.62	1.58	7.8	0.6	5 M	12	12	12	12.4
7	May 20, 1938	0.4	6.5	11.5	5.0	0.57	0.57	8.8	0.6	3 M,L	8	11	11	5.0
8	May 21, 1938	0.6	4.6	11.2	6.6	0.72	0.72	9.2	0.7	3 M	10	10	10	6.6
9	June 16, 1938	0.35	0.6	16.3	15.7	2.06	2.00	7.8	0.7	4 L	7	12	12	15.7
10	Oct. 20, 1938	-0.6	-0.6	-0.6	0.0	0.70	----	---	---	9 M	--	--	--	----
11	Nov. 5, 1938	-0.6	-0.5	-0.1	0.4	0.85	----	---	---	6 M	--	--	--	----
12	Feb. 3, 1939	0.5	1.2	17.4	16.2	2.32	2.30	7.0	1.2	20 M,U	16	15	11	20.2
13	Mar. 5, 1939	0.55	0.8	12.1	11.3	1.40	1.33	8.5	1.1	11 M	13	13	11	12.2
14	Apr. 15, 1939	0.55	0.7	20.2	19.5	3.46	3.42	5.7	1.2	40 M,U	22	20	11	32.5
15	May 20, 1939	-0.3	-0.1	0.3	0.4	0.79	----	---	---	6 M	--	--	--	----
16	Sep. 5, 1939	-0.75	-0.7	0.5	1.2	1.01	----	---	---	2 M,L	--	--	--	----
17	Sep. 29, 1939	-0.7	-0.7	-0.4	0.3	0.78	----	---	---	8 M	--	--	--	----
18	Oct. 1, 1939	-0.6	-0.5	0.3	0.8	0.97	----	---	---	8 M	--	--	--	----
19	Oct. 26, 1939	-0.7	-0.6	0.2	0.8	1.09	----	---	---	10 M	--	--	--	----
20	Oct. 27, 1939	-0.6	-0.3	5.8	6.1	1.50	1.38	4.4	0.3	6 U	16	14	13	7.1

Virginia). The determination of the duration of rainfall, column (k), and the breakdown of multiple storms into simple ones were based on two recording rain-gages near the watershed, Buchannon and Freemansburg, West Virginia. These recording rain-gages were installed in October, 1937. For storms prior to this date, hourly records of rainfall at Elkins and Clarksburg, West Virginia, were used.

Column (h) gives values of precipitation minus initial loss, $(P - L_1)$. The maximum value of initial loss was fixed at 0.90 inch for an index ground-water stage of -0.7 foot and a temperature of 70° F on a basis of storms 10, 11, 15, 16, 17, 18, and 19. The minimum or zero-value of initial loss was assumed for an index ground-water stage of 1.04 feet which is the ground-water stage on the ground-water depletion-curve four days after the maximum of two feet. The variation of initial loss with index ground-water stage is shown on Figure 2. The amounts of initial loss used to obtain the values of $(P - L_1)$ were adjusted for antecedent rainfall within a period of six days.

The ground-water stage depletion-curve was developed in the usual manner from a study of stage-heights during periods of little or no direct runoff. The depletion-curve is not shown on any of the illustrations, but the following points define it: 2.0 feet at zero-time; 1.42 feet at two days; 1.04 feet at four days; 0.68 foot at seven days; 0.18 foot at 14 days; -0.25 foot at 24 days; and -0.70 foot at 52 days.

The final ground-water stage, column (j), was determined from plotted stage-hydrographs of the various stream-rises and represents ground-water recharge (J, Fig. 1). The final ground-water stages for the component parts of multiple storms were estimated by proportioning the total recharge among the individual storms.

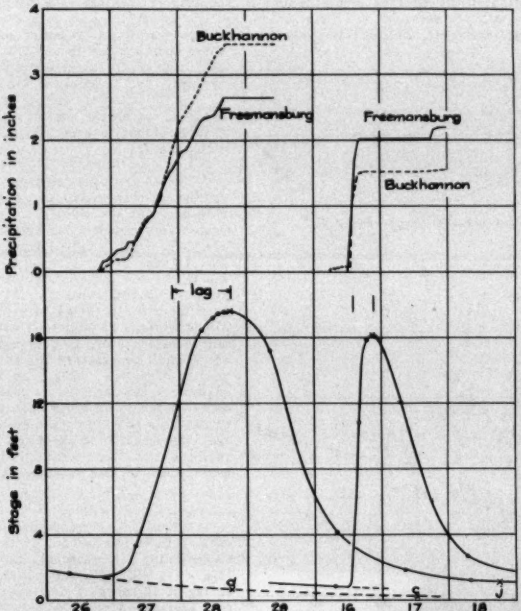

FIG. 1-STAGE-HYDROGRAPHS FOR WEST FORK RIVER ABOVE WESTON, W. VA.

Column (k) gives the duration of precipitation for the storms and includes an identifying letter, namely, L for lower, M for middle, U for upper, to indicate the section of the watershed which had the greatest precipitation. The use of the letter M indicates that the precipitation was either fairly uniform or greatest on the central part of the drainage-basin.

The observed lag is given in column (m). Lag is defined as the time in hours from center of mass of surface-runoff-producing rainfall to crest-stage. The value of lag determined for this basin by synthetic procedure [1] is 12 hours, based on a channel-length, L, of 30 miles and a stream-distance to center of area of 15 miles and the average coefficient of two; lag = $2(30 \times 15)^{0.3} = 12.2$ hours. A basin of this size and lag requires a unit-duration of rainfall of about three hours for use with a regular unit-hydrograph procedure. A three-hour synthetic unit-hydrograph would have a duration of four and one-half days.

Column (n) gives the values of lag which are the result of adjusting the observed values for areal variation in amounts of rainfall. This is an attempt to eliminate the effect of areal distribution of rainfall on the values of lag. The values of lag in column (n) are all assumed to be the result of uniformly distributed storms. The greatest adjustment, five hours, has been made to the lag for storm No. 9 of June 16, 1938. The precipitation measured for this storm at the two stations farthest from Weston was 1.09 and 1.13 inches and at the two nearest stations was 3.17 and 3.06 inches.

From an inspection of the data in Table 1, it is apparent that duration of precipitation is the remaining factor having an appreciable effect on the value of lag. As would be expected, the very small rises are exceptions and have greater values of lag than accounted for by the distribution or duration of rainfall.

In the section of the paper on synthetic unit-hydrographs [1] dealing with the application of the procedure to flood-forecasting it was stated that the assumption of a constant value of lag for a drainage-basin was not consistent with regular unit-hydrograph procedure and it was shown that, in the latter procedure, lag increased as the duration of rainfall increased. For large areas the effect of duration of rainfall on lag is not so evident, but on the small basin under consideration its effect is clearly demonstrated.

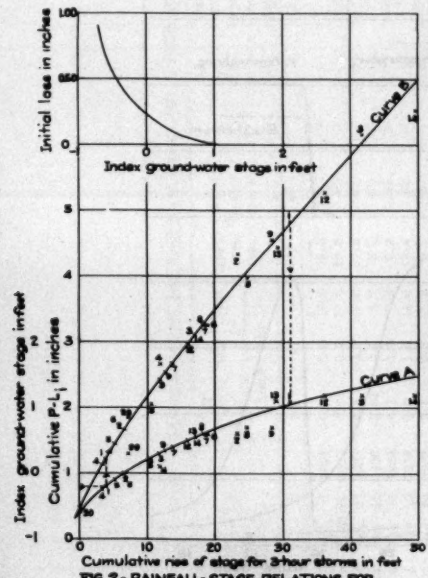

FIG. 2 - RAINFALL-STAGE RELATIONS FOR WEST FORK RIVER ABOVE WESTON, W.VA.

In the previous paper the unit-hydrograph peak discharge for a storm of unit-duration was made (K/t_p) and the adjusted value adopted for longer storms was $[K/t_p + (t_R - t_r)/4]$ where t_p was the lag, t_r was the duration of a unit-storm, and t_R was the actual duration of surface-runoff-producing rainfall. It now appears that the denominator of this expression is also the means of adjusting the lag for a unit-duration storm to correspond to that which would be expected for storms of greater duration. Using this basis of adjustment the lag for the West Fork River above Weston is 12 hours (for a three-hour storm) plus one-fourth the number of hours that the duration of any storm is greater than the unit-storm duration of three hours, that is, the adjusted lag, $t_{pR} = [t_p + (t_R - t_r)/4]$.

Column (o), corresponding lag for a unit or three-hour storm, is thus obtained by reversing the procedure, that is, $t_p = [t_{pR} - (t_R - 3)/4]$. The synthetic value of lag of 12 hours is thus seen to be a fair average.

In the synthetic unit-hydrograph

procedure the unit-hydrograph crest-discharge for any unit-duration would be equal to (K/t_{pR}). This relation provides a means of adjusting the observed crest-rises of column (f) to the values that would be expected if the storms had occurred in the unit-duration of time of three hours. The adjusted crest-rise is equal to $(t_{pR}/12)$ times the observed crest-rise. The adjusted values of crest-rise are given in column (p). No adjustments to crest-rise are made unless the values of t_{pR} are greater than the normal lag of 12 hours (t_p).

The final step is the correlation of the adjusted values of crest-rise with precipitation and index ground-water stage. Curve A, Figure 2, shows the variation of cumulative rise of stage with index ground-water stage. The curve is developed by first assuming a trial-line and then plotting the observed data. A low value of stage of -0.7 foot was taken as the initial or beginning point for the relations. In plotting storm No. 1, the trial-curve is entered with the index ground-water stage of -0.2 foot and an initial value of cumulative rise of stage of 4.0 feet is noted. The adjusted crest-rise of 27.0 feet is added to the initial value of 4.0 to obtain the final value of cumulative rise of stage of 31.0 feet. The final value of cumulative rise of stage, 31.0 feet, is then plotted against the final ground-water stage of 1.1 feet. After the data for all the storms have been plotted in a similar manner, trial-curve A is redrawn to obtain a better correlation and the data are replotted.

Curve B is developed next by drawing a trial-curve and plotting the available data using the index ground-water stage and curve A to fix the initial values. Storm No. 1 with an index ground-water stage of -0.2 foot and curve A give an initial value of cumulative rise of stage of 4.0 feet. Trial-curve B is entered with this value of 4.0 and the initial value of cumulative $(P - L_1)$ of 1.22 inches is obtained. The $(P - L_1)$ for the storm, 3.62 inches, is added to the initial value of 1.22 and a final value of 4.84 inches is obtained. This value of 4.84 inches is then plotted against the previously determined final value of cumulative rise of stage of 31.0 feet. After all the data are plotted, trial-curve A is redrawn and the process is repeated until the best fit is obtained.

Figure 2 shows the final curves and the plotting of the data in Table 1. The initial points are indicated by a small cross-bar on curves A and B with the number of the storm noted nearby. The plotting of the final values are also identified by number.

In using the curves of Figure 2, the above steps are reversed. The cumulative rise of stage is determined for the given storm assuming it occurred in three hours with a lag of 12 hours. The actual lag to be expected is determined from the actual duration of the surface-runoff-producing rain $(P - L_1)$ and equals $[12 + (t_R - 3)/4]$. The value of crest-rise obtained from Figure 2 is adjusted to correspond to the expected lag and added to the base-stage to obtain the predicted crest-stage. The adjusted lag, t_{pR}, is further adjusted if the rainfall is not uniformly distributed, thus establishing the time of cresting.

The correlation of the data for curve A is not as good as that for curve B. This is the usual situation since curve A represents ground-water recharge and additional refinements are required for more accurate results. In the present usage, the ground-water recharge is of minor importance and curve A is used primarily as a means of entering curve B.

The data defining curve B correlate very well. The curve corresponds to rainfall-runoff relations in a more refined procedure. If rainfall-runoff relations and a unit-hydrograph are available for a watershed, rainfall-stage relations can be computed. In addition to saving time in making forecasts, the principal advantage of the rainfall-stage relations over rainfall-runoff relations is their tendency toward a constant slope. Curve B of Figure 2 snows a range in the value of unit crest-rise from 6 to 8.5 feet per inch. If the lower section for values of index ground-water stage less than zero is disregarded, the variation of unit crest-rise is from 7 to 8.5 feet.

The tendency of curve B to take a constant slope is evidently due to the fact that the small percentages of surface-runoff, occurring when index ground-water stages are low, are counterbalanced by the smaller increases in discharge necessary to raise the stage a given amount at the usual gaging station.

When the values of unit crest-rise are constant or differ slightly for various index ground-water stages (soil-conditions) curves A and B are not needed for making predictions. In such a case the determination of soil-conditions (index ground-water stages) has no effect on the results except as it influences the choice of initial loss. Even when curve B has a slight curvature, errors in the assumption that index ground-water stage accurately represents soil-conditions have little effect on the resulting crest-predictions.

The procedure is considered to give good results for the basin used in this example. Since the normal lag is only 12 hours, multiple crests or decided changes in rate of rise are produced when the rain stops or undergoes decided changes of intensity for periods of 12 hours or longer. For best results such storms should be treated separately and this requires that the stage-recessions following successive periods of rise be estimated or based on an average recession-curve. A convenient basis for estimating recessions at Weston is the fact that the river-stage usually falls from any crest-stage to a stage of less than four feet in 1-1/2 days. This item becomes of minor importance for larger drainage-basins.

The amount of adjustment involved in correcting values of lag and crest-rise for the duration of rainfall also decreases as the drainage-area and lag increase Crest-rises for a watershed having a lag of 24 hours would be adjusted from zero to 21 per cent for storms varying from 6 to 24 hours in duration.

The upper limit of drainage-basin size to which the procedure is applicable is the same as would apply to the regular rainfall-runoff relation and unit-hydrograph procedure. This limit is usually controlled by rainfall-characteristics.

References

[1] F. F. Snyder, Synthetic unit-graphs, Trans. Amer. Geophys. Union, 19th annual meeting, Part I, pp. 447-454, 1938.
[2] F. F. Snyder, A conception of runoff-phenomena, Trans. Amer. Geophys. Union, 20th annual meeting, Part IV, pp. 725-737, 1939.

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ON THE STATISTICAL ANALYSIS OF RAINFALL-DATA

Herbert C. S. Thom

Introduction--Statistical analysis is generally considered to be divided into two parts, the part called mathematical probability and the corroborative part sometimes called applied statistics. The first part being a mathematical theory is responsible only to its postulates and is not related directly to practical application. The second part, however, consists of the interpretation and application of the abstract concepts of mathematical probability and is the bridge required to connect mathematical probability and practical problems. A simple example of the relation between pure mathematics and the solution of practical problems is the application of ordinary euclidean geometry. It is well known that in solving a problem using euclidean geometry the "elements" of the problem must first be shown to reasonably correspond with the "elements" of the postulates, that is, the point, line, and plane. Likewise, in solving a problem by mathematical probability the "elements" of the problem must agree with the "elements" of the postulates of mathematical probability. If this condition is not satisfied an incorrect solution will result, just as it would in euclidean geometry when the "elements" are not good approximations of points, lines, and planes. It should be remembered that mathematically speaking no set of "elements" of a system of postulates can be identical with the elements of a practical problem. There are, however, close approximations that allow mathematical theory to be used in practical problems and it is the question of sufficiency of approximation on which applications of mathematics rests. The misapplication of statistical analysis, as well as any mathematical theory, is very often due to the lack of agreement between the "elements" of the postulates and those of the problem.

There are several systems of postulates on which mathematical probability may be based, the most common of which are a priori theory and relative-frequency theory. Taking the casting of dice as a simple example whose "elements" agree closely with the "elements" of the postulates of the two systems in question, the a priori theory regards the probability of certain events occurring when the dice are cast as measuring some quality inherent in the dice. The relative-frequency theory, on the other hand, postulates a limiting process in which the ratio of the number of trials approaches infinity. Before even a start toward a solution can be made, the latter theory requires a large amount of data that often is not available or not easy to compile. In recent years, mainly through the influence of the writings of Kolmogoroff [see 1 of "References" at end of paper], Fréchet [2], and Cramér [3], mathematical probability has been returning to the a priori theory. This it appears is the most logical and least misunderstood basis for mathematical probability. It is the foundation on which statistical mechanics was largely de-

veloped and is also the most desirable from an engineering standpoint where data are often scarce and reasoning must necessarily proceed from the cause to the effect. The a priori system was constantly in mind when the studies reported in this paper were made.

The postulates of this a priori system are stated below as given in Harald Cramér's "Random variables and probability distributions."

"Denoting by R_k a k-dimensional euclidean space with the variable point $X = (x_1, \ldots x_k)$ the family of all Borel sets S in R_k are considered.

"Axiom I--To every S corresponds a non-negative number P(S), which is called the probability of the relation (or event) $X \subset S$.

"Axiom II--$P(R_k) = 1$.

"Axiom III--P(S) is a completely additive set function, that is, $(P(S_1+S_2+\ldots) = [P(S_1) + P(S_2) + \ldots]$ where S_1, S_2, ... are Borel sets, no two of which have a common point. The variable point X is called a random variable."

A statistical theory of rainfall--Problems solvable by means of statistics may be described generally as follows: Given an assembly of things and consider one definite property of the things; suppose that this property can be described in terms of one or more definite quantities that can be graduated in intervals. In this way there is obtained a plurality of states to be distinguished from each other. The problem then arises as to how under any given conditions the things will be distributed among the different states [4]. Each quantity is a random variable as defined above.

The assembly of things in the point-rainfall problem are the storms which occur over the point. The property considered in this problem is the amount of rainfall falling from a storm in a given duration, and the quantity measuring it is the depth of rain falling at the point. An assembly of things or objects and properties satisfying axioms I to III is all called a probability-field. Thus a storm might have the property of having a maximum depth of 2.00 inches for a fixed duration of say 24 hours. An event is the condition of a storm having a certain property. The storm-paths are random with respect to the point and therefore the depth of rainfall is a random variable in accordance with Axiom I.

It will be noted that the axioms do not mention the independence of events so often confused in engineering writings. This is because it was desired to have a system of axioms which would apply generally, that is, to absolute as well as conditional probabilities, so that the distribution-functions apply for both conditional and absolute probabilities. Since the rainfall-event at a point, unlike the flood-rise, is inherently an independent event, the frequency-curves in this discussion have been prepared for independent events. When tabulating the point-rainfall data used, the independence of the events was assured through meteorological considerations.

There are two characteristics of rain-producing storms which together give rise to the frequency-distribution of rainfall at a point--one is the random movements of storms with respect to the point, and the other is the distribution of magnitude of the storms with respect to their volumes and the concentration of their volumes for a given duration. If all storms occurring over a point produced identical rainfall-patterns for a given duration, then the frequency-distribution of rainfall at the point would be identical with the distribution of rainfall-depths within the storm-pattern. If one casts a die which has its two replaced by an ace, in a long series of castings there will be approximately twice as many aces thrown as any other number of the die. Likewise with the above storm-pattern, if there is twice as much area between the one- and two-inch isohyets as there is between the four- and five-inch isohyets, there will be twice as many occurrences at a point between one and two inches as there are between four and five inches. This rather simple picture, however, is not the complete story; there still remains the question of the distribution of magnitude and concentration to be taken into account.

The two distributions may be combined by tabulating the areas between successive isohyets of, for example, one-half-inch intervals for all storms producing rain at the point. With the assumption of randomness of rainfall in mind, it can be seen that the total area for all storms between successive isohyet-values will be directly proportional to the probability of occurrence at the point. The area considered would be limited to a meteorologically homogeneous region (discussed later) with approximately constant mean annual rainfall.

The extreme skewness of the point-rainfall frequency-distribution can be explained as partly due to Lexian variability, that is, variation of the probability over a series of storm-patterns. This results from the second distribution mentioned above.

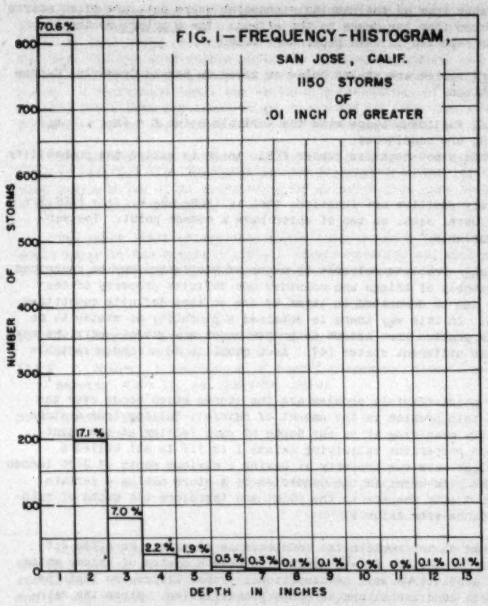
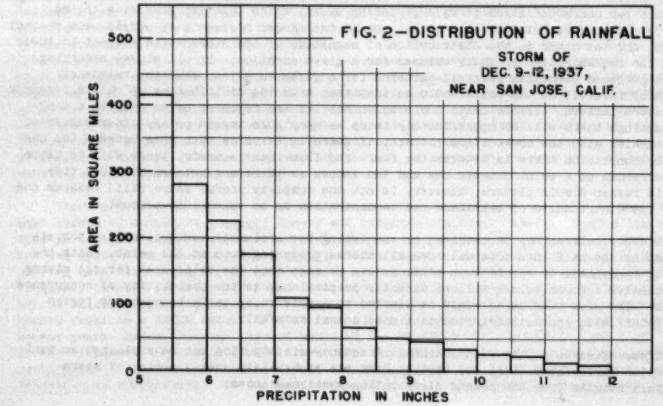


Figure 1 shows an actual frequency-histogram for 72-hour rainfall occurring in 1,150 storms at San Jose, California. The storm-event is chosen so that it is independent of any past or future occurrences and 72-hour rainfall also includes rainfall of any duration less than or equal to 72 hours. The latter condition has been included to take care of extension to areal rainfall-frequency. Figure 2 shows the histogram of depth against area for the portion of the storm of December 9 to 12, 1937, included in a meteorologically homogeneous region without constant mean annual rainfall. The resemblance to the frequency-histogram of Figure 1 should be noted. Depth decreases as area increases in Figure 2 and depth decreases as frequency occurrence increases in Figure 1. The distribution with respect to time resembles the distribution with respect to area. This is in accordance with the theory set forth above.

Meteorological homogeneity--The term rainfall-frequency, as employed in this paper, is to be interpreted in the usual manner, that is, a rainfall-frequency of T years for depth d in duration t means that a depth d in duration t is reached or exceeded on the average once in T years. The set of rainfall-events occurring in a record is a random set, that is, the events are variable quantities with a definite range of values, each of which can occur with a definite probability. Thus, using rainfall-frequency nomenclature, one



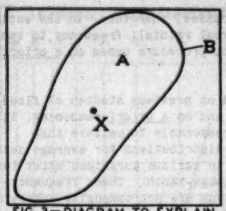


FIG. 3—DIAGRAM TO EXPLAIN SIGNIFICANCE OF RAINFALL-CAUSES

inch of rainfall occurring in 24 hours may be reached or exceeded once on the average each year, and if there is an average of 27 storms per year there are approximately four chances in 100 that a storm will equal or exceed one inch in 24 hours. It can be readily seen that this probability of four chances in 100 is the integral of the frequency-distribution between the limits one inch and the physical upper limit of rainfall.

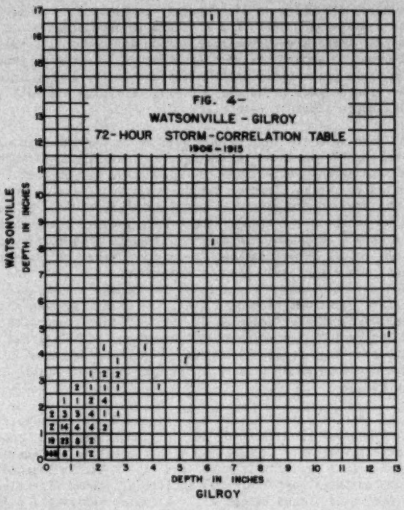
It has been observed in previous studies that point-rainfall frequency-curves for stations in the same vicinity resemble each other to a considerable extent. Such resemblance is not fortuitous but can be logically explained by the interaction of the causes of rainfall. To explain the significance of rainfall-causes, it is convenient to consider a region A with boundary-curve B having a station X within A as shown in Figure 3. Through frequency-studies made at points along B it is found that all points have identical frequency-curves. Suppose a thorough consideration of storm-morphology from a physical aspect, independent of the station-records, gives adequate reason to believe that the chance-causes (that is, random causes) of producing rainfall of all possible depths and durations over area A will be identical even when A is of considerable area. Since the chance-causes are functions of the intrinsic properties of the storm-systems and are independent of the region over which the storms pass, it is logical to conclude that every point of A should have identical frequency-curves if only chance-causes are operating. A region such as A, in which the chance-cause system is the same at every point, is defined as a meteorologically homogeneous region.

Suppose then that a frequency-study is also made for station X in Figure 3 and it is found that its frequency-curves are appreciably different from those of points along boundary B. Since the region A has been established to be meteorologically homogeneous with respect to the chance-causes of producing a given depth of rainfall in a duration of time, the fact that the chances of producing that depth at X are different indicates that there are additional causes affecting X which do not affect stations along B. These additional causes will be called assignable causes. Evidently the assignable causes are characteristic of X rather than of the series of storms affecting area A. They are a measure of the difference between the frequency-characteristics of X and those along B all in a meteorologically homogeneous region. The assignable causes may have the effect of producing either more or less rainfall at X. If they were not operating, X would have frequency-curves identical with stations on B.

Obviously examples such as shown in Figure 3, where numerous stations have identical frequency-curves and where statistical study of the station-records can be used to establish meteorological homogeneity will be rare in practice. Meteorological homogeneity must then, in general, be established by meteorological studies. In order to make use of the above concepts, it is then necessary to start with a known condition of meteorological homogeneity. Since this condition is not based on station-records, all stations within the region may have different frequency-curves; these differences being due entirely to assignable causes at the stations themselves.

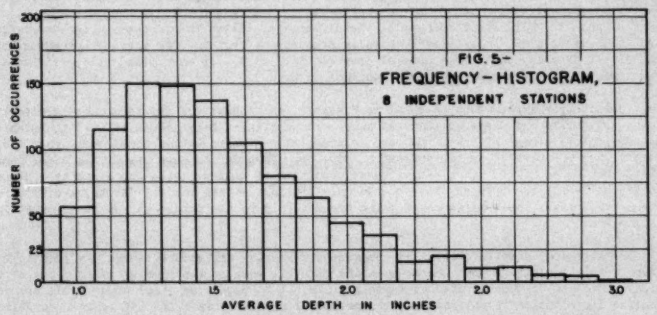
If a region is meteorologically homogeneous, and the assignable causes are identical at every point, it follows that the mean annual rainfall must be the same at every point of the region. This can be demonstrated by assuming rainfall to have a physical upper limit and considering the distribution (identical at every point) of point-rainfall for the longest duration storm which occurs over the region. The integral of this frequency-distribution divided by the number of years of record will give the mean annual rainfall. If the chance-cause system is the same but the assignable causes vary over the region then the mean annual rainfall will also vary. This variation in mean annual rainfall will be proportional, in a statistical sense, to the variation in the assignable causes or to the variation in the frequency-curves. This characteristic of the meteorologically homogeneous region furnishes a means of extrapolating rainfall-frequency characteristics over the region. It should not be concluded from any of the above discussion that chance and assignable causes of rainfall have been explained physically. It has only been necessary and possible thus far to classify causes as chance or assignable.

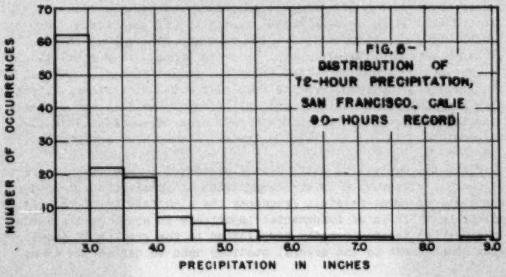
Areal rainfall-frequency--The difficulties presented in the computation of point-rainfall frequency are greatly accentuated in the computation of areal rainfall-frequency. It is readily seen that, whereas with point-rainfall frequency the simultaneity of the station-records is comparatively unimportant, it is of fundamental importance in areal rainfall-frequency. The concept of the storm-event becomes greatly complicated in the problem of areal rainfall as does the relation of the storm-event to the several stations used to define the event. It is all the

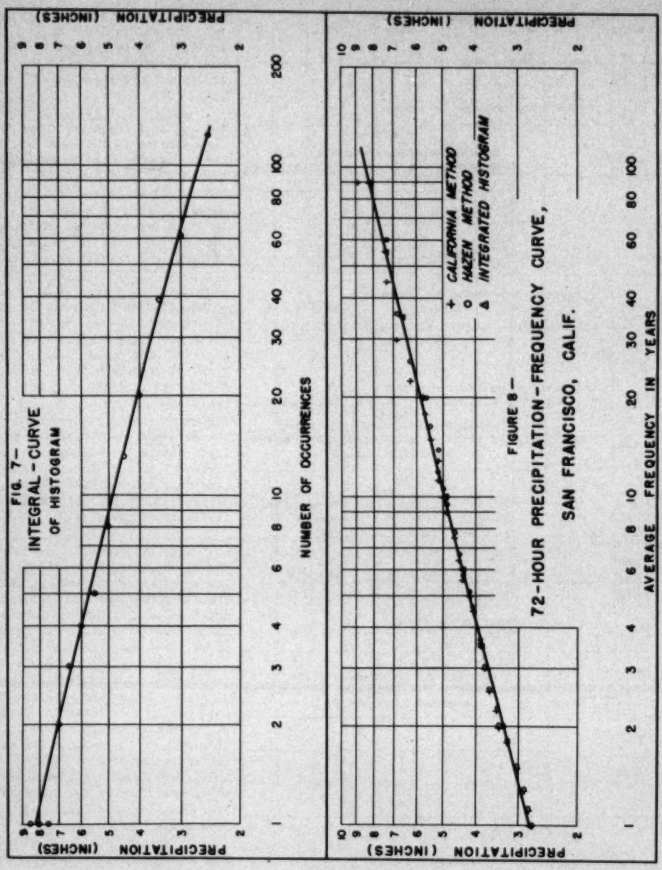


more imperative, therefore, in the estimation of areal rainfall-frequency to employ an indirect procedure based on a priori reasoning.

Based on previous studies of flood-frequency and on a priori reasoning, it is entirely reasonable to believe that frequency-distributions for average depth or volume in various durations exist for a given drainage-basin. These frequency-distributions are not composite curves derived from the station frequency-curves by considering the station rainfall-events from a given storm as independent because of correlation between the several stations. This correlation results from two causes: First, the average depths of a series of storms occurring in a record will be distributed in a frequency-function with the result that storms with greater average depths will, in general, produce greater depths at the several stations; second, the centers of action of a storm-system, although being random in position, have considerable area and a tendency to move in a general west-east direction so that stations in the path of a center will experience greater depths than those not in the path. Thus, when one station re-

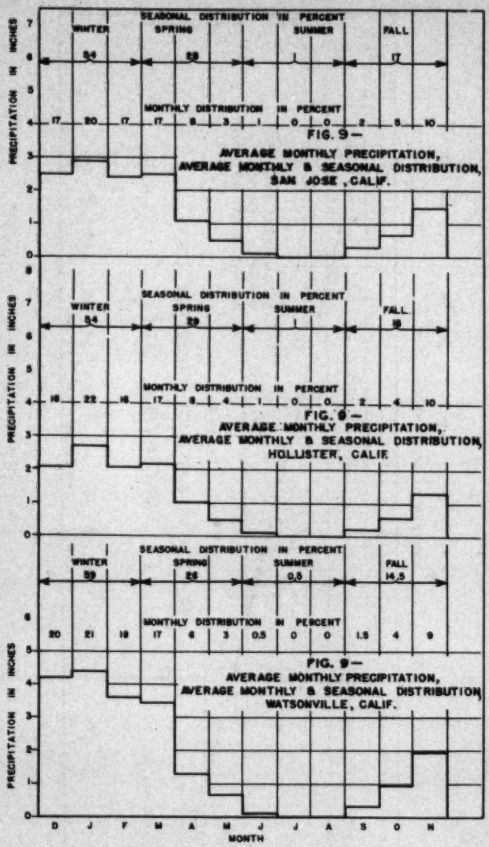






ceives a depth above the average, the chances are better than even that an adjacent station will also receive an amount above the average. The correlation between simultaneous rainfall-depth at Watsonville and Gilroy is shown in Figure 4. These two stations were chosen because of their similarity in mean annual rainfall.

The frequency-distribution of areal rainfall for a given basin must therefore lie between two limiting conditions, (1) the condition of perfect correlation and (2) the condition of statistical independence. The condition of perfect correlation will approach the most frequently occurring point-rainfall distribution-curve in the basin while the condition of statistical independence will be represented by a composite frequency-distribution formed through considering the volume of rainfall on the basin to be measured by a number of stations which are independent of each other. Figure 5 shows a frequency-histogram composed by the drawing of 1,000 samples of eight volumes from eight independent populations representing the rainfall-frequency distribution


SEASONAL DISTRIBUTION IN PERCENT
WINTER 54
SPRING 29
SUMMER 1
FALL 17
MONTHLY DISTRIBUTION IN PERCENT
17 20 17 17 8 3 1 0 0 2 8 10
PRECIPITATION IN INCHES
FIG. 5— AVERAGE MONTHLY PRECIPITATION, AVERAGE MONTHLY & SEASONAL DISTRIBUTION, SAN JOSE, CALIF.
SEASONAL DISTRIBUTION IN PERCENT
WINTER 54
SPRING 29
SUMMER 1
FALL 16
MONTHLY DISTRIBUTION IN PERCENT
16 22 16 17 8 4 1 0 0 2 4 10
PRECIPITATION IN INCHES
FIG. 6— AVERAGE MONTHLY PRECIPITATION, AVERAGE MONTHLY & SEASONAL DISTRIBUTION, HOLLISTER, CALIF.
SEASONAL DISTRIBUTION IN PERCENT
WINTER 59
SPRING 26
SUMMER 0.5
FALL 14.5
MONTHLY DISTRIBUTION IN PERCENT
20 21 18 17 6 3 0.5 0 0 1.5 4 9
PRECIPITATION IN INCHES
FIG. 7— AVERAGE MONTHLY PRECIPITATION, AVERAGE MONTHLY & SEASONAL DISTRIBUTION, WATSONVILLE, CALIF.
D J F M A M J J A S O N
MONTH

at eight evenly spaced stations over the Pajaro River Basin. Each station is assumed to always measure the average for the area it represents.

Analysis of rainfall-data--The rainfall-frequency curve is very similar to the duration-curve commonly used in engineering work of various kinds. It has the disadvantage that reliability varies with duration and in usual procedures of plotting, such as the Hazen or "California" methods, the fitted curve with its plotted points gives an exaggerated impression of accuracy which has been a constant source of argument between statisticians and engineers [5]. It is believed from a statistical point of view to be more satisfactory to deal directly with the frequency-distribution or histogram, using it to smooth the data and then integrating it to obtain the rainfall-frequency curve. Through this procedure the engineer is better enabled to evaluate the reliability of his data.

Figure 6 shows a frequency-histogram for 72-hour rainfall and a record of 90 years at San Francisco, California. A class-interval of 0.5 inch has been chosen for the histogram. This is believed to be as small as is warranted by rainfall-data in general. The integrated curve of Figure 7 has been obtained by integrating the histogram, that is, by simply adding the blocks of Figure 6. A smooth curve was fitted to the data of Figure 7 and Figure 8 was obtained from it by transforming the abscissa from an occurrence-scale to a time-scale. Data computed by the "California" and Hazen methods also have been plotted on Figure 8. It will be noted that the two other methods of plotting check closely with the curve drawn to the integrated points.

While at the present time there is no a priori theoretical distribution-function for rainfall-data, it is hoped that studies now being carried on by the Hydrometeorological Section of the United States Weather Bureau will produce such a function. This will greatly enhance the value of the histogram method of plotting frequency-curves.

Extrapolation of rainfall frequency-curves--In the following analysis the concept of meteorological homogeneity is employed in extrapolating frequency-curves over the Pajaro River Basin, California.

Meteorological homogeneity, as pointed out above, can be only established by a thorough

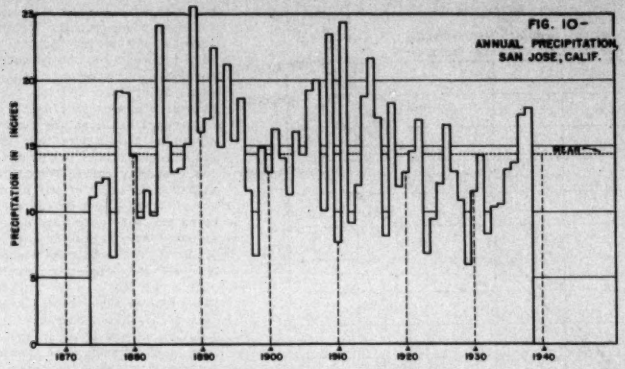


FIG. 10— ANNUAL PRECIPITATION, SAN JOSE, CALIF.

study of the storm-morphology of the region. There are, however, certain statistical data which can be used to corroborate the meteorological studies. For example, the fact that all points of a region have very nearly the same number of days with 0.01 inch of rainfall or more is an indication that each point of the region will be visited by about the same number of storms; although it is, of course, obvious that the day has little relation to the storm-period, and that therefore there will be, in general, more rainy days than storms. Also a storm-situation (one favorable for rain) which prevails over the region may be so weak as to produce rainfall at only such stations which have significant local effects favoring increased rainfall, as orographic effects. Thus these stations will, in general, experience more rainy days than do those stations with assignable causes of lesser magnitude. The following major characteristics lead to the belief that the region including the Pajaro River Basin and Santa Clara County is meteorologically homogeneous: (1) A single type of storm produces rainfall over the region, as was established through meteorological studies; (2) there are meteorological reasons for believing that all points of the region will be subjected to storm-conditions with about equal frequency; (3) a similar seasonal regimen of rainfall prevails over the region as shown by Figure 9.

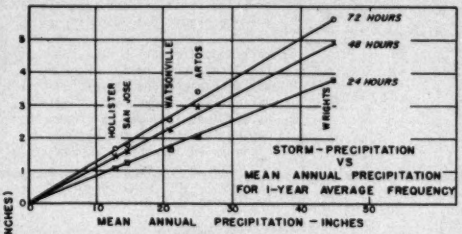
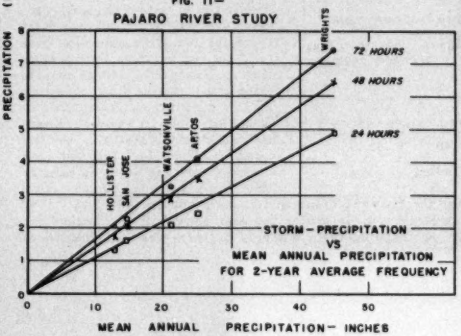
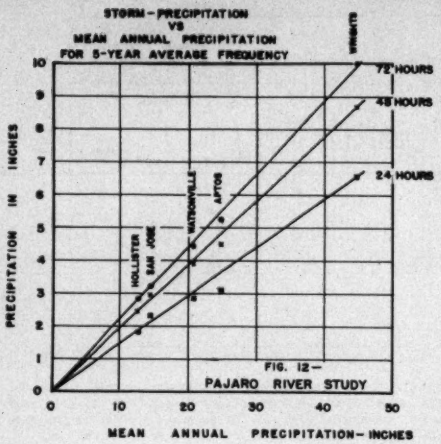


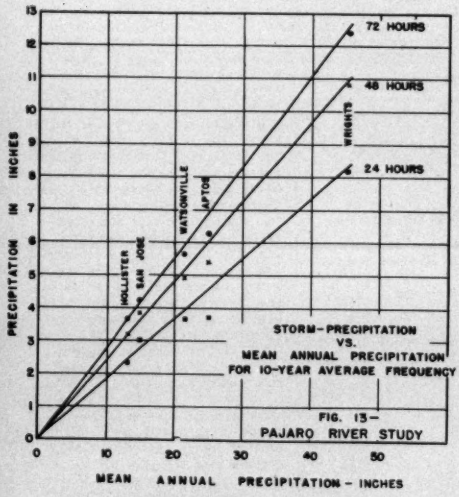
FIG. 11— PAJARO RIVER STUDY



Corroborative evidence--The number of days with 0.01 inch or more of precipitation is fairly uniform over the region.

The records for Hollister, Watsonville, Aptos, and Wrights were such that frequency-studies could be made only for storms of 24-, 48-, and 72-hour durations because these stations recorded precipitation once a day. It is obvious that storms, which are more or less random in nature, do not





coincide with the period between the times of observations. It is therefore to be expected that the rainfall recorded for the 24-hour observation-period will always be equal to or less than that for the 24-hour storm-period, and that this difference would become less for storms of longer duration. Since it was essential that use be made of the frequency-curves for the above stations, a study of the effect of an arbitrary storm-period was made, using the automatic rainfall-record at San Jose. Frequency-curves were prepared from arbitrary 24-hour rainfall and from actual storm-period rainfall. A comparison of these showed that the differences were negligible compared with the sampling errors involved and, therefore, there is adequate reason to believe that these frequency-curves reasonably approach the accuracy of those prepared from first-order station records.

In order to define a set of frequency-curves for every point in the basin, the relationship between mean annual rainfall and frequency-duration-depth as discussed above was employed. The means of annual rainfall for the various stations were adjusted to the stations having the longer records by comparing simultaneous periods of record. The variability of mean annual rainfall at San Jose is shown in Figure 10. Depths of rainfall for various frequencies and durations as read from the frequency-curves were then plotted against mean annual rainfall in Figures 11, 12, and 13.

As would be expected from the discussion of meteorological homogeneity, there exist average relationships between mean annual rainfall and depth for various frequencies and durations. These relationships can be employed in constructing the duration-curves or frequency-curves to apply to the mean annual rainfall-classification of the basin shown in Figure 14. This map was prepared from the adjusted mean annual rainfall-values at the several stations. To find the frequency-depth-duration relationship for any point in the basin it is only necessary to locate that point on Figure 14, determine the mean annual rainfall-class, and then choose the proper set of curves. As these curves are simply ordinary rainfall frequency-curves, they are not produced here.

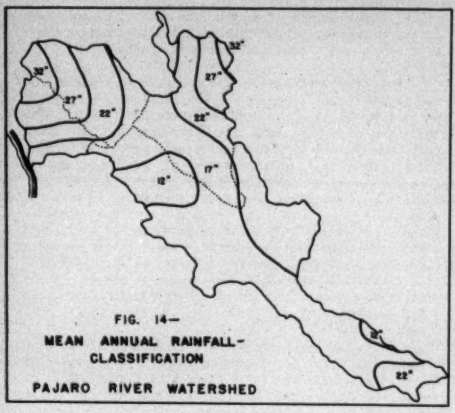


FIG. 14—
MEAN ANNUAL RAINFALL-
CLASSIFICATION
PAJARO RIVER WATERSHED

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U. S. Weather Bureau,
Washington, D. C.

EROSIONAL LAND-SLOPE-PROFILE SHAPE IN TERMS OF THE EROSIVE POWER OF RAINFALL-RUNOFF

James M. Little

This paper is to be published elsewhere.

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Berkeley, California

THE EFFECT OF CONTOUR-CULTIVATION ON RUNOFF

H. C. Knoblauch and J. L. Haynes

The effect of contour-planting on the rate of runoff, silt-load capacity, and depression-storage are important factors in erosion- and flood-control. Results of the practice must be considered by soil conservationists, agricultural engineers, and hydrologists in planning erosion and flood-control measures for watersheds or for individual farms. Since contour-tillage reduces erosion and frequently results in increased crop-yield, the practical application is of importance to the farmer.

Very little previous work has been done on the rate of runoff from small-plot areas under conditions of natural rainfall. However, experiments with artificial rainfall have been carried on by some investigators. Water applied at a uniform rate was studied by Woodruff, Smith, and Whitt [see 4 of "references" at end of paper] to determine the effect of various factors in connection with an evaluation of runoff-hydrographs. They noted considerable variation in hydrographs under different conditions of soil-surface configurations.

Borst and Woodburn [1], in investigating contour-cultivation with the rainfall-simulator, accounted for differences in soil-loss through the increased storage-capacity by contour-ridges. Even after the ridge was broken, they reported an observed reduction in velocity of flow and a continuation of deposition.

A comparison of runoff-phenomena expressed in runoff-intensity, surface-detention, and depression-storage is made between contour-tillage of corn and tillage with the slope by means of hydrographs. Results are presented for various conditions of soil and rainfall as they existed at different seasons of the year. Records were obtained during 1938 and 1939 at the Beemerville Soil Conservation Experiment Station, Sussex, New Jersey. The soil at this station is classified as Dutchess stony loam. The surface-layer to a depth of eight inches is open and

Fig. 1--Plot planted on contour from which runoff-graphs were collected

Fig. 2--Plot planted with slope from which runoff-intensities were compared with records of contoured planting

allows rapid passage of water. The subsoil becomes relatively compact and impervious at about 18 inches. The plot areas have a moderate degree of erosion.

Procedure--Hydrographs given herein were taken from two 14 by 70 foot corn plots. The contour-planted plot has a slope of 16.8 per cent while the plot planted with the slope is 16 per cent. The areas used for this study have been planted to corn continuously since 1937. Rows are 42 inches apart with plants in the row approximately nine inches apart. Contour-ridges constructed through cultivation-operations are about four inches in height with an 8- to 12-inch base. Figure 1 is a photograph taken in December, 1938, that illustrates the surface-condition on the contour-planted plots. It can be observed that the interspacings have filled with silt to some extent and the ridges have broken in places. It will be noted that opportunity for depression-storage is still evident.

Conditions under tillage with the slope are shown by a photograph (Fig. 2). There is very little opportunity for depression-storage under these conditions. Small shoestring gullies have been formed on either side of the base of each drill-row as a result of cultivator-marks left by the last cultivation and concentration of water from the corn-plants.

Plant-cover, soil-treatment, planting, cultivation, and harvest are similar on both plots. The only introduced variable is direction of tillage with reference to slope. Rates of runoff were measured with six-inch type-H flumes equipped with float-type water-stage recorders.

The method of hydrograph-analysis used was basically that presented by Horton [2, 3]. Refinements were made in the method for a determination of the retention-rate for adaptation to the extremely sensitive runoff-graphs obtained from small-plot areas.

The assumptions used in the analysis of the data presented in this paper are as follows:

(1) Retention-rate is assumed to be constant during runoff under rainfall in excess of average retention-rate.
(2) Depression-storage is assumed to have been completed at the start of runoff.
(3) Rates of infiltration, evaporation, and interception are included in rate of retention.

These are essentially the assumptions underlying Horton's method of hydrograph-analysis. However, in preparing the present paper, the following modifications were made in Horton's method:

(1) The submergence-factor was expressed as a variable subject to evaluation by field-observations.
(2) Subsurface-detention was treated separately from surface-detention.
(3) Recognition was made of varying percolation-rate during the interval described by Horton [2] as the period of residual rainfall.

To facilitate an understanding of terms used in this discussion, the following definitions are given:

Surface-detention: Depth of water detained on soil-surface which eventually runs off.
Depression-storage: Depth of water impounded by depressions on the surface and which is permanently retained.
Surface-storage: Total depth of water on soil-surface, or the sum of depression-storage and surface-detention.
Subsurface-detention: Water which is temporarily retained in the soil but reaches the surface as seeps, joining with surface-runoff.
Submergence-factor: Fraction of the surface covered by detention during recession [2].

This study is concerned only with the effects of contour-cultivation on the rate of runoff and the volume of surface-storage. For this reason, only the data on surface-detention and rate of runoff are presented.

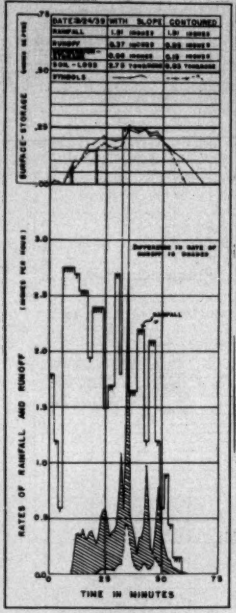

Fig. 3--Hydrograph of high-intensity storm on very dry soil (8-24-39)

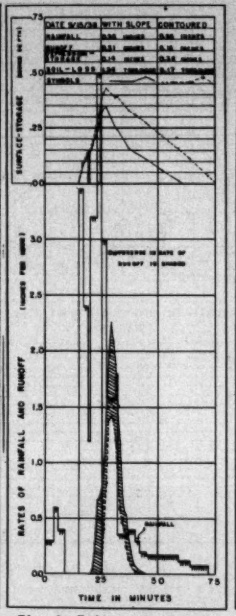

Fig. 4--Hydrograph of high-intensity storm on moist soil (9-15-38)

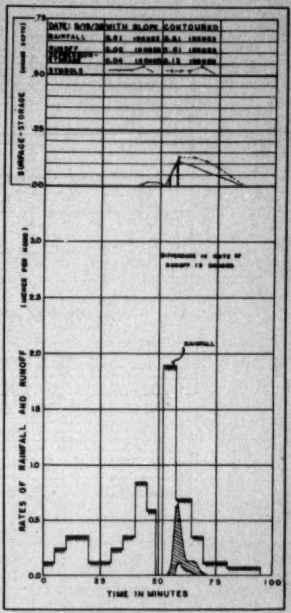

Fig. 5--Hydrograph of moderate-intensity storm on wet soil (9-19-38)

Results--The hydrograph given in Figure 3 for August 24, 1939, was the result of a summer thunder-shower of high intensity. The soil was very dry. Samples showed an eight per cent moisture-content in the upper six inches of soil. Due to previous prolonged drought-conditions, the subsoil was also very dry. The corn-crop on the plots at this time was about six feet in height and afforded a ground cover of from 40 to 50 per cent. Ridges on the contour-plot were in good condition, having had no runoff subsequent to the last cultivation. The plot planted with the slope had well-defined channels in the interspace caused by three previous runoff-periods. Data on retention-rate, peak-flow, and density of runoff for this as well as other storms in this study are presented in Table 1. According to the theory that all depressions are

Table 1--Comparison of retention-rate, peak-flow, and density of runoff from corn planted with the slope and on the contour

Date of runoff	Precip-itation	On contour			With slope		
		Retention-rate	Peak-flow	Density-runoff	Retention-rate	Peak-flow	Density-runoff
	inches	in per hr	cfs	lb. soil per cf	in per hr	cfs	lb. soil per cf
Aug. 24, 1939	1.81	1.93	0.010	0.31	1.52	0.061	4.16
Sep. 15, 1938	0.95	0.84	0.032	0.60	0.98	0.046	2.46
Sep. 19, 1938	0.61	0.62	0.003	*	0.62	0.015	*
Sep. 21, 1938	2.31	0.28	0.019	0.16	0.24	0.023	0.48
Dec. 5, 1938	1.49	0.13	0.018	0.13	0.10	0.022	0.33

*Measurements of soil-losses were not made.

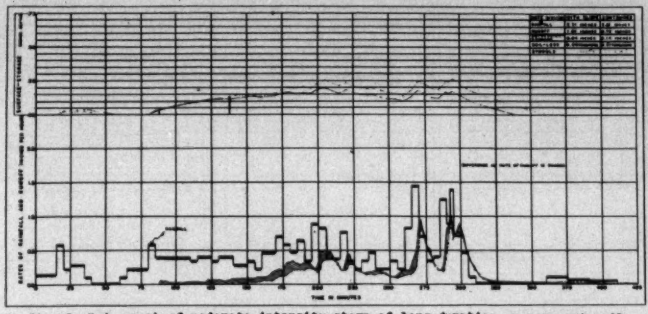

Fig. 6--Hydrograph of moderate-intensity storm of long duration on very wet soil (9-21-38)

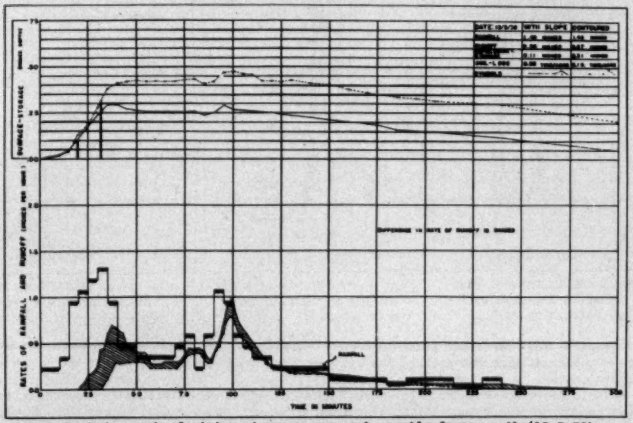

Fig. 7--Hydrograph of winter storm on very wet, partly frozen soil (12-5-38)

filled at the start of runoff, depression-storage for the contour-plot indicates a capacity of 0.07-inch greater depth of storage than obtained from up-slope and down-slope tillage. Reductions of velocity and consequent lead-capacity of the runoff are apparent. The 4.16 pounds of soil per cubic foot of runoff on the plot planted with the slope and 0.31 pound of soil per cubic foot of runoff for the contour-area indicate a ratio of over 13 to 1.

Runoff from a storm of intensity somewhat comparable to the storm of August 24, 1939, but with a higher moisture-content in the topsoil, is given in Figure 4. This storm took place on September 15, 1938. The subsoil was relatively dry. Silage-corn had been harvested before the date of this storm. Four previous runoff-periods had occurred subsequent to the last cultivation of corn. The total runoff was 1.67 inches on the planting with the slope and 0.55 inch on corn drilled across the slope. Shoestring gullies had been formed on either side of the drill-rows running with the slope. Contour-ridges on the lower quarter of the contour-plot were broken, at intervals, from previous storms. There was, however, still considerable opportunity for storage.

The retention-rate for the storm of September 15, 1938, is of special interest in that the contoured plot has usually given a higher retention-rate than on the planting with the slope.

Surface storage-capacity was found to be 0.24 inch greater under contour-planting.

Runoff from wet soil is illustrated by Figure 5 for a storm of moderate intensity occurring on September 19, 1938. Precipitation of 1.30 inches on September 18 and 19 preceded the runoff-record. Both surface and subsoil were relatively moist. Contour-ridges were broken in at least one place in each drill-row on the lower three-quarters of the slope-length by runoff from the storm of September 15, 1939. Considerable silting had taken place in the drill-row interspacings of the contour-plot and a more pronounced drainage-system had formed on both plots. Figure 5 gives a storage capacity of 0.09 inch due to the contours. No density-measurements were made for this storm due to continued precipitation.

The record of the hurricane of September 21, 1938, given in Figure 6, is an illustration of runoff-behavior under a condition of very high soil-moisture. Both the surface and subsoil were wet before this record, due to a 4.16-inch rainfall on the two days preceding. The difference in density of flow indicated in Table 1 is noteworthy, in view of the fact that rates of flow approach uniformity. It is also interesting to note that peaks of runoff-intensity on the contoured plot, especially during the first half of the storm, are more rounded than on the plot drilled up and down the slope. Residual runoff during the last hundred minutes shown on the hydrograph was observed to have been caused by surface-discharge from a perched water-table.

Figure 7 shows runoff under winter conditions for a storm on December 5, 1938. Rains totaling 1.08 inches on December 4 and 5 had caused considerable thawing of the soil. Prior to the rains of December 4 and 5, the soil had been frozen to a depth of 12 inches since November 29. At the end of runoff on December 5, ice-crystals and localized frost-concentrations were to be found at 8- to 12-inch depths on the plots. The upper six inches were entirely thawed. The photographs shown in Figures 1 and 2 were taken on December 15 and show the condition of the drill-row ridges at the time of this record. A difference in storage capacity of 0.20-inch depth is indicated in Figure 7. Retention-rate and peak-flow are given in Table 1.

Discussion--Inspection of the hydrograph given in Figure 3 indicates that runoff may have started on the lower part of the plot before depression-storage was satisfied on the upper part of the plot. Should this be the case, the actual storage capacity on the contour-ridges would be somewhat higher than indicated by the figures. Error introduced by length of slope resulting from the assumption that storage is satisfied at the start of runoff is accentuated on areas with contoured depressions when previous runoffs have formed channels which drain surface-reservoirs at the lower end of the slope. This error affects the calculations of retention-rate as well as those of surface-detention and depression-storage according to present methods of computation.

The runoff-condition shown in Figure 4, where the retention-rate on the plot planted up and down the slope exceeds the contour-planted plot, seems to be due to a higher soil-moisture content on the contoured plot as indicated by the soil-moisture measurements. This greater moisture-content can undoubtedly be explained as a consequence of greater moisture-retention on the contoured plot as a result of a previous rainfall which caused runoff on the plot planted with the slope. The simplicity of character of the storm tends to minimize the error due to length of slope in the determination of surface-capacity. The differences in depression-storage for this storm, therefore, would be expected to closely approximate the actual storage-capacity of the contour-ridges. It is also probable that the high initial intensity caused runoff before the infiltration-rate reached a constant, in which case the figures for surface-detention preceding and at the start of runoff would be too high for records given on both plots.

The breaking of contours and silting of interspacings apparently reduced the storage capacity of the contours approximately one-half for the storm of September 19, 1938, when compared with the recorded capacity of the rainfall of September 15, 1938.

The hydrographs from the storm of September 21, 1938, indicate that the retention-rate decreases toward the end of the storm and that the rates for the two plots appear to become almost alike. The storage capacity compares closely with the amount indicated for the storm of September 19, 1938. This is to be expected since there was very little change in surface-character of the respective plots between the two storms.

The low retention-rate for the storm of December 5, 1938, was probably due to the presence of frost-crystals in the soil, puddling of the surface-soil due to the thawing action, and to the high moisture-content of the soil. The only changes to the surface-horizons of the plot-soils subsequent to the record of September 21, were due to the action of frost and runoff. This action may have caused disruption of the former drainage-pattern, thus partly accounting for differences in surface-detention.

Attempted solution for the roughness-coefficient n, according to methods suggested by Horton [2] gave results which showed wide fluctuation within single storms. It is apparent that further refinement of Horton's formula is necessary before practical application can be made on records from small-plot areas of the nature described herein. A part of the difficulty experienced in making calculations for the coefficients as described by Horton was caused by the lack of uniform distribution of water over the entire surface of the plot due to the character of plot-surface resulting from the tillage-practices under consideration. Further difficulty is experienced due to the wide fluctuation of character of channel-bed covered by flow with differences in depth of water on the plot during a single storm.

Assumption of a constant retention-rate during runoff affords a convenient working point upon which to base computations of other components of hydrologic phenomena but the error introduced by this assumption is sufficiently great to cause serious departure from accuracy in determination of surface-detention and depression-storage. This error is accentuated when runoff starts from a dry soil and is particularly large at the initial stage of the storm.

The general problem calls for further investigation to identify and evaluate more properly the mechanics of flow and sediment-suspension which are the direct result of tillage-practices affecting configuration of soil-surfaces.

Summary--Hydrographs are presented showing comparison of rate of flow, surface-detention, and depression-storage of contoured and up-and-down tillage practices under summer- and winter-type storms and for various conditions of soil-moisture and surface.

Storage capacity obtained by contour-tillage of a 16 per cent slope was found to be approximately 0.20-inch depth before breaking contours by runoff. Storage capacity was reduced by breaking of the contour-ridges to approximately 0.09-inch depth.

Attempts at calculation of roughness-coefficients showed that present methodology for determination of these values is not satisfactory for records from small plots with uneven surface-configurations.

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Joint contribution from the Soil Conservation Service and the New Jersey Agricultural Experiment Station, New Brunswick, New Jersey

REPORT ON DEFICIENCIES IN HYDROLOGIC RESEARCH

Thorndike Saville

The members of the Section of Hydrology of the American Geophysical Union will find on the desk in the registration office copies of a new report entitled "Deficiencies in hydrologic research" which has just come today from the Government Printing Office. I believe that members of this Section will be particularly interested in this report, and perhaps a little review of its antecedents will not be out of place.

Stimulus toward the expansion of national undertakings in the hydrological research field may be said to have begun with the work of the Mississippi Valley Committee in 1934. At that time attention was called in the very elaborate report prepared by the Committee to the grave lack of hydrologic data in planning for large-scale water-undertakings. As a result largely of the points of view brought out in this report, the successor to the Mississippi Valley Committee, the National Resources Committee, established under the direction of its Water Resources Committee a special Advisory Committee on Hydrologic Data. This Committee surveyed in a rather intensive fashion the entire situation from a national standpoint the deficiencies in basic hydrologic data

which existed in the country. Through the cooperation of Government agencies and competent consultants, the Advisory Committee produced a report in 1936 which undertook to present the existing status of the collection and publication of hydrologic data in the United States and to make recommendations for supplementing such data by expanded programs. As a result of this report, several of the Federal agencies were able to secure funds for carrying out in part or entirely specific recommendations in this report.

One of the major points of view brought out during the preparation of this report on deficiencies in hydrologic data was the lack of any coordination in hydrologic research, and the need for stimulation in particular fields of such research. As a result, the Water Resources Committee of the National Resources Planning Board asked the Advisory Committee on Hydrologic Data to undertake the preparation of a report on "Deficiencies in hydrologic research." This is the report which is now before you, and which has been in preparation for some two and a half years. Manifestly, as you all are aware, hydrologic research is advancing so rapidly on so many fronts that any report must be out of date in some respects when it is issued. You will find, therefore, certain deficiencies within this report on deficiencies, but I hope you will realize that if the Committee had waited to have every suggestion with respect to research right up to date, the report would never have been issued.

May I say that the constitution of this Advisory Committee on Hydrologic Data (all of the members of which are members of this Section) has appeared to me as one of the most effective means for carrying out advisory and coordinating functions with respect to Government agencies which involve various agencies and various fields of interest. The Committee was constituted from the scientific representatives of the principal Federal agencies concerned with hydrologic data and a number of consulting engineers from private practice representing various parts of the country, and familiar with the problems of those regions. This Committee has, therefore, brought to its task not only a great variety of scientific knowledge, but has been able to reconcile various views which differed both as between the several Government agencies and as between regional problems and interests. Naturally the report which you will receive is something in the nature of a compromise. It was subjected to review by two prominent consulting engineers, and was submitted for comment to some 40 or 50 engineers particularly conversant with the problems discussed. As a result, it is hoped the report may stimulate research in hydrology along more or less coordinated lines, and may be helpful in calling to the attention of those who may desire to undertake research specific topics which are believed to be important and useful.

To my mind one of the most important recommendations of the report relates to the necessity for some type of clearing house for hydrologic research undertakings. It seems a great pity that Federal and State agencies and others engaged in hydrologic research so frequently go ahead on extremely interesting and valuable studies, without any knowledge of what another agency or individual is doing, without knowledge of the methodology which may have been developed elsewhere, without information as to the availability of data which is to be found buried in the files of some agency or individual, all of which represents a vast waste of time and effort. Furthermore, our practice in the past has been to individualize research both on the part of agencies and individuals to such an extent that there is not only duplication of effort, but frequently much time has been lost in developing procedures which may already be known elsewhere, but which have not appeared in print. All of this might be greatly simplified if some central office could act as a clearing house for information as to what research was in progress or contemplated, and where those who were intending to prosecute research could write to find out what other agencies or individuals were doing, how they were doing it, what their objectives were, and what they had accomplished to date. All of this would save time and effort, and would unquestionably permit a greater effectiveness and friendliness in carrying on much of the hydrologic research which is still so badly needed in this country. I bespeak your good offices in stimulating in whatever way seems best to you the establishment of such a clearing house of information with respect to undertakings in hydrologic research.

College of Engineering, New York University,
Water Resources Committee, National Resources Planning Board,
New York, New York

THE INFLUENCE OF A LODGEPOLE-PINE FOREST ON STORAGE AND MELTING OF SNOW

H. G. Wilm and M. H. Collet

In the central Rocky Mountains exists a particularly important relation between snow, forest-cover, and stream-flow. Rate and volume of stream-flow depend to a great extent on ac-

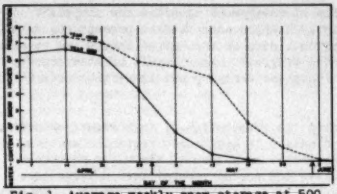

Fig. 1--Average weekly snow-storage at 500 snow-stakes

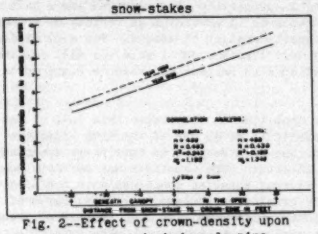

Fig. 2--Effect of crown-density upon snow-storage in Lodgepole pine

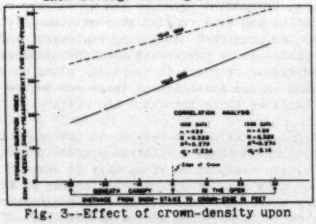

Fig. 3--Effect of crown-density upon snow-melt in Lodgepole pine

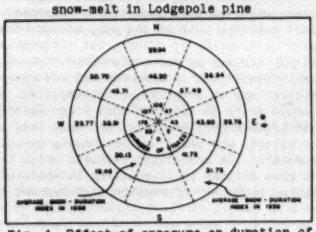

Fig. 4--Effect of exposure on duration of snow-storage in a Lodgepole-pine forest

cumulation and melting of snow. Snow-conditions, in turn, are associated directly with forest-cover. All of these elements combine into a complex interrelationship that can be understood only through processes of careful research.

To meet the need for research in this field, the Forest Service has started a program of long-time studies in the Rocky Mountains, concentrated for the present in the widely distributed and commercially important lodgepole-pine type. As a site for the first of these studies an area was selected on the Fraser Experimental Forest, near Fraser, Colorado, on the headwaters of the Colorado River. The principal forest-cover on this experimental forest is mature lodgepole-pine, with Engelmann spruce and alpine fir as secondary species.

The phase of the study discussed herein is confined to 20 five-acre plots established for the purpose of studying the influence of various methods of cutting timber on forest-growth, as well as on storage and melting of snow. As a first step the plots were established and observed in a natural condition for two years, during which detailed measurements of snow-conditions were taken. After this two-year period, the plots were cut-over by four different methods, leaving stands of widely different densities. Snow-measurements for several years after cutting will test the influence of the several cutting methods on snow-storage. This paper, confined to results of two-years' study of snow on the plots in their natural condition, presents information on the influence of natural variation in density of the forest-canopy upon accumulation and melting of snow.

Methods--On each of the 20 plots a series of 25 stakes was mechanically distributed as permanent points of snow-measurements. Each snow-stake was carefully described as to crown-cover, exposure, slope per cent, and position on the slope relative to bounding ridges. With 25 stakes on each plot and a total of 500 on the 100 acres involved, a good representation was secured of all crown-conditions occurring within the stand.

Weekly snow-measurements were taken at each of the stakes during the spring of 1938 and 1939. These measurements were for the purpose of determining the amount of water present in accumulated snow prior to and during the period of spring melt. All measurements were obtained with the Utah snow-sampling equipment; observational technique followed that recommended by the Utah Agricultural Experiment Station [George D. Clyde, Establishing snow courses and making snow surveys, Utah Agric. Exp. Sta. Circ. 91, illus., 1930].

The average water-content of snow was computed for each plot for each week during the melting period and for each season for all plots. In addition, correlation-analyses were made by individual years, to determine the influence of crown-canopy density and other factors on storage and rate of melt.

Independent variables and symbols used in the correlation-analysis were: (a) Distance from

stake to crown edge in feet, plus if stake is in the open and minus if under a crown; (b) percentage of ground slope at the stake; (c) vertical distance in feet between valley-bottom and ridge of the slope upon which the stake was located; (d) vertical distance of stake below the ridge; and (e) exposure at the stake, coded and expressed as a numerical value.

Because of the predominant northwest exposure of the study-area, most of the snow-stakes are on slopes facing in a northerly direction, with very few stakes on southerly slopes (Fig. 4). For this reason the effects of general exposure cannot be brought out adequately in this study. Still, it was considered advisable to measure the effects of existing variations in exposure by coding and incorporating this variable in the correlation-analysis.

Dependent variables in the analyses were (1) water-content of the stored snow prior to the melt-period (x_1), and (2) storage-duration index (x_2). This index, simply the sum of water-contents for all measurements in a given season at each stake, serves to integrate both initial storage and duration of snow-melt at the stake.

Results--The average water-content of snow accumulated at all the stakes in the spring of 1938 was 7.33 inches, a figure somewhat in excess of that for 1939, when only 6.38 inches were stored. In 1938, snow remained on the ground an average period of 14 days longer than it did in the spring of 1939 (Fig. 1). A probable cause for the longer period of melt in 1938 was the occurrence of several light snow-storms after April 28 of that year and the generally cooler weather prevailing during the 1938 melt-period.

Some interesting relationships became evident when analysis was made of the correlation of certain site factors with snow stored at each of the 500 snow-stakes. Water stored in snow was at a minimum under the largest crown clumps and reached a maximum in the largest available openings, where the snow-stakes are about 30 feet outside the edges of adjoining crowns (Fig. 2). This relation between water-content of the snow and crown proximity can be expressed by a straight line, with a correlation-coefficient (R) of 0.493 in 1938 and 0.430 in 1939. For the conditions of this study, site factors such as exposure, steepness of slope, and position of each stake on the slope apparently failed to exert any significant influence.

The storage-duration index for a given stake, derived by summing weekly snow-measurements during the melt-period, provides a composite figure which expresses both the volume of storage and the rate of melt. A high initial amount of stored snow melting over a long period of time, for example, would give a maximum value for the index; a low initial storage and rapid rate of melt would give a minimum value. This index is actually more important than simply the volume of snow stored at the beginning of the spring melting season, as rates and duration of spring and summer stream-flow should be largely dependent on the persistence of snow-cover through the spring.

Analysis of 1938 and 1939 storage-duration data by individual stakes developed significant relationships (Fig. 3). Together the two factors of canopy density and exposure accounted for 28 per cent of the variation in the storage-duration index (R = 0.528 in 1938, 0.529 in 1939). Slope-percentage, slope-height, and position on the slope had little or no determinable effect upon the duration of snow-storage.

Because of the general northwest slope on which the study was located, the influence of exposure (other than north, northwest, and west) was probably minimized, although the index increases from a minimum in the southwest to a maximum in the northeast (Fig. 4). In the northeast octant, for example, 47 snow-stakes showed average storage-duration indices of 57.49 in 1938 and 36.54 in 1939, while 23 stakes in the opposite (southwest) octant gave corresponding values of only 30.13 and 19.46.

Altnough the influence of crown density upon both initial snow-storage and the storage-duration index was found to be highly significant on a statistical basis in both 1938 and 1939, it might be well to point out that a large part of experimental variation must be attributed to uncontrolled variables and to error. Some of the factors which may be responsible for the unaccountable variation are: (1) Winter drifting and leveling of the snow; (2) experimental error due to inaccuracies in the measuring equipment; (3) uncontrolled errors in the measuring technique; and (4) poor representation of exposures to each of the four cardinal directions.

A significant feature of the study is the fact that the relation of existing crown densities to both initial snow-storage and the storage-duration index may be expressed as a straight line. Since no flattening of the curve of relationship occurs even for the largest available openings, it may be concluded that optimum conditions for snow-storage and melting are not found in this

uncut stand of lodgepole-pine. A logical inference is that some degree of thinning of the forest should provide even greater storage than occurred in the largest openings available for study. The fact that the stakes are located in a mature lodgepole-stand where the average height of the dominant trees is about 70 feet may help to explain the favorable storage-conditions provided in existing large openings. In such stands it is quite possible that openings with radii of about 30 feet are relatively small enough so that they remain shaded throughout the greater part of the short winter days, thereby permitting only a limited amount of evaporation and melting to take place. Initial storage would naturally be less in smaller openings and beneath the canopy because of higher interception-evaporation losses.

Conclusions--Two-years' observations of snow-storage in a mature lodgepole-pine forest have resulted in establishment of the following facts:

(1) Canopy density is an important stand factor affecting snow-storage and melting in lodgepole-pine stands.
(2) Slope-percentage, slope-height, and position on the slope have little or no measurable effect upon volume of stored snow in well-stocked lodgepole-stands.
(3) Since snow-storage and melt-duration were at a maximum in the largest canopy openings studied, it would appear that the size of opening providing maximum storage in mature lodgepole-stands has a radius of 30 feet or more.

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RECESSION OF GLACIERS IN GLACIER NATIONAL PARK, MONTANA

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Recent detailed mapping by the National Park Service of several glaciers in Glacier National Park, Montana, has yielded much information about the volume-shrinkage of these glaciers since the area was mapped by the United States Geological Survey in 1900-02. To date, three glaciers, Grinnell, Sperry, and Jackson have been mapped by the plane-table-and-stadia method on a scale of 1:2400. The work was begun late in August 1937 with the mapping of Grinnell Glacier [see 1 of "References" at end of paper]. Sperry was mapped in August 1938, and Jackson in August 1939. A resurvey of each glacier every five years is contemplated, so that an accurate check on the total amount of ice-shrinkage may be maintained.

The Chief Mountain, Montana, topographic sheet of the United States Geological Survey which shows these glaciers, as mapped in 1900-02, on a scale of 1:125,000 is too generalized to be of much use in comparing the glaciers in 1900-02 with their counterparts on the new large-scale maps. However, by means of the older, small-scale map and photographs taken about 1900, the approximate borders of the glaciers at that time have been located and placed upon the new maps. Construction of longitudinal and transverse profiles with this information as a guide gives an approximate indication of the amount of surface-lowering and thus the volume-shrinkage since 1900-02. The following determinations have been made with respect to the recession of these recently mapped glaciers in Glacier National Park:

Grinnell Glacier--In 1900-02 the Glacier had a surface-area of about 0.93 square mile. Shrinkage of the ice since then has caused the Glacier to separate into two parts. In 1937 the lower and larger of these two ice-masses had a surface-area of about 0.51 square mile. The upper ice-mass, although not mapped in 1937, was estimated to have a surface-area not exceeding 0.04 square mile. Thus, the total area from 1900-02 to 1937 was reduced by 0.38 square mile, or 40 per cent.

The amount of shrinkage in area, however, has probably been considerably less than the volume-decrease during the same period. Photographs of Grinnell Glacier taken in 1897, the earliest thus far obtained, show that the Glacier then was about 300 feet thick at the point where its north edge lay in 1937. Comparison of recent observations with those of Alden [2], made in 1911, indicate that the ice was about 80 to 100 feet thick at the point where the terminus was in 1937. Further, the surface of the Glacier at the cirque-headwall was lowered by an amount varying between 45 and 90 feet from 1911 to 1937.

Thus, although its surface-area has decreased about 40 per cent, Grinnell Glacier, in the past 40 years, may have lost considerably more than 50 per cent of its volume.

Fig. 1--Jackson Glacier as it appeared in 1901
(Photograph by F. E. Matthes)

Fig. 2--Jackson Glacier as it appeared in 1939
(Photograph by F. E. Matthes)

Sperry Glacier--This Glacier, which at present may be the largest single ice-mass in Glacier National Park, in 1900-02 possessed a surface-area of about 1.31 square miles. Between that time and 1938, shrinkage of the Glacier has caused it to separate into several ice-masses, the largest of which has a surface-area of 0.61 square mile. The most prominent of the smaller ice-bodies, which lies at the east base of Mount Edwards and which was contiguous with the main Glacier until 1938, now has a surface-area of 0.04 square mile. Thus the present area of the Glacier represents only about 47 per cent of the area it had in 1900-02.

Jackson Glacier--In 1900-02 this Glacier, which then was joined to the Blackfoot Glacier, possessed a surface-area of approximately 1.25 square miles, and a length of about one and one-half miles. When mapped in August 1939, it was separated from the Blackfoot Glacier by a distance of about one-half mile, its length had been reduced to one mile, and its surface-area to 0.29 square mile. In 1900-02 the ice at the site of the present terminus of the Glacier was about 200 feet thick, and at a point 1,000 feet upstream from the position of the present terminus the ice was at least 100 feet thicker than in 1939. Forty years ago the terminus rested at an elevation between 5,800 and 5,900 feet, whereas when mapped in 1939 it lay at an elevation of 6,440 feet.

Retreat of this Glacier has exposed a uniformly sloping surface which is a dip-slope of massive limestone. It apparently continues under much, if not all, of the present Glacier with a dip nearly equal to the angle of slope of the Glacier's surface and in the same direction. Thus, the Glacier appears to have a very uniform thickness, probably being no thicker in any part than it is a short distance back from its terminus. The fact that ablation, in the upper part of the Glacier, has caused the rock-floor to emerge above the ice-surface in several places during the past two years bears out the above conclusion. Unless a distinct climatic change occurs, the Jackson Glacier may disappear almost entirely within the next ten years.

Other glaciers--Wentworth and Delo [3], probably basing their conclusions upon information taken from the Chief Mountain Quadrangle of the United States Geological Survey (1900-02), stated that the group of glaciers consisting of the Blackfoot, Harrison, and Pumpelly, together with the Sperry, about three miles to the northwest, had a combined surface-area of about seven square miles. However, all these glaciers have shrunk notably in size since 1900. Harrison Glacier has receded until it is now not much more than a narrow strip of firn along the base of the south wall of Mount Jackson. The combined area of these glaciers, which in 1900-02 was seven square miles, is now probably less than three square miles. Whereas in 1900-02 there were eight or nine glaciers in Glacier National Park which had surface-areas of one square mile or more, there probably is none of that size today. Furthermore, there are probably less than nine with surface-areas exceeding one-half of a square mile.

For some reason not entirely apparent to the writer, recession of glaciers in Glacier National Park seems to be more rapid than of glaciers farther south in other ranges of the Rocky Mountains and in the Sierra Nevada.

References

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[2] Glaciers of Glacier National Park, U. S. Dep. Int., 1914.
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A YEAR OF EVAPORATION FROM A NATURAL LAND-SURFACE

C. W. Thornthwaite and Benjamin Holzman

The evaporation-station situated on the Experimental Farm at Arlington, Virginia, has been in continuous operation for more than a year. The station is designed to measure the evapotranspiration losses from a natural land-surface and has been described elsewhere [see 1, 2, 3 of "References" at end of paper].

The observations of precipitation, evaporation, and condensation at Arlington are summarized by months for 1939 in Table 1. The data for February and September are missing because of the interruption of the observations by instrumental failure and the installation of new equipment. The values for evapo-transpiration and condensation are based upon continuous records of the moisture-gradient in the atmosphere and the coefficient of turbulent exchange. Using these parameters the vapor-transport to and from the ground is determined by hourly intervals and then summed to obtain the value for the day. (In all the evaporation-determinations the value 0.38 has been used for von Kármán's universal turbulence-coefficient. Since there are no atmospheric data to corroborate this dimensionless constant, the actual values for evapo-transpiration and condensation may be somewhat in error. There is some evidence indicating that the value 0.40 should be used. This would increase the amounts of evapo-transpiration and condensation by a constant amount, approximately ten per cent, since the universal constant enters into the computation as a squared quantity.) The total precipitation for the ten months amounted to 26.34 inches. The moisture-contribution to the ground by condensation of dew or frost was 1.77 inches. The return of moisture to the atmosphere due to combined evaporation and transpiration was 11.88 inches. By subtracting the evapo-transpiration from the sum of the precipitation and condensation a value of 16.23 inches is obtained for runoff and increase in ground-storage.

In winter, transpiration is greatly suppressed. Moreover, low ground-temperatures along with intermittent snow-cover keep the losses of moisture from the ground at a minimum. When vegetation approaches maturity in summer, the transpiration-losses become maximal. Thus in June moisture-losses to the atmosphere were five times as great as in January. Although still quite high in July and August, losses were reduced through mowing of the ground-cover over which the station is located.

Table 1--Exchange of moisture between the ground and the atmosphere, Arlington, Virginia, 1939

Month	Precipitation	Condensation	Evaporation
	inches	inches	inches
January	3.41	0.06	0.48
February[1]	....	....	....
March	2.81	0.03	0.92
April	2.93	0.31	1.07
May	0.20	0.11	1.65
June	5.87	0.25	2.44
July	2.16	0.28	1.93
August	2.98	0.16	1.46
September[1]	....	....	....
October	2.38	0.24	0.79
November	1.40	0.22	0.59
December	2.20	0.11	0.55
Total[2]	26.34	1.77	11.88

[1]Incomplete record. [2]Total for ten months having complete records.

Water stored as soil-moisture was reduced nearly an inch and a half by evaporation and transpiration in May when only 0.2 inch of rain fell. However, much of this soil-moisture loss was restored by a rain of 1.77 inches on June 8 and on June 13 with a rain of 1.88 inches, of which 1.51 inches fell in a single hour.

In general, precipitation at Arlington in winter is nearly as great as in summer. Frequently a good portion of the winter precipitation is stored on the ground as snow. Since the evapo-transpiration losses are at a minimum in winter, the chances for general floods to occur in the colder seasons are greatly enhanced. Actually, the flood-hazard is greatest in early spring when evaporation-losses are still quite small, and warm rains, together with the melting of accumulated winter snow may cause considerable amounts of runoff.

The losses of moisture into continental and maritime air-masses during June and July, 1939, are shown in Table 2. Those days in which air-mass changes or obscure air-mass transitions occurred were omitted. Although the maritime air was considerably warmer than continental air, its daily rate of intake of moisture from the ground was only 58 per cent as great. Maritime air flowing northward over the Continent from tropical latitudes is warm and moist and contributes considerable amounts of dew-condensation to the land. Continental air flowing southward from polar regions is characterized by dryness and turbulent winds and thus induces the optimum conditions for evaporation from the land.

Table 2--Exchanges of water-vapor between the ground and continental and maritime air-masses during June and July, 1939, Arlington Experiment Station

Date	Air-mass type	Number of days	Average temperature	Total evaporation	Total condensation	Total loss from ground	Average daily loss from ground
			°	inches	inches	inches	inches
June, 1939	Continental	10	74.0	0.8887	0.0075	0.8812	0.0881
	Maritime	11	76.4	0.7182	0.1507	0.5675	0.0516
July, 1939	Continental	12	72.7	0.9740	0.0695	0.9045	0.0754
	Maritime	14	79.2	0.7878	0.1670	0.6208	0.0443

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THE EVAPORATION-ENERGY EQUATIONS AND THEIR PRACTICAL APPLICATION

N. W. Cummings

Synopsis--The average daily evaporation from Bear Lake in Utah and Idaho has been found to be 0.23 inch of depth, which is four per cent more than the simultaneous Weather Bureau pan-reading. A thermally insulated pan lost 0.24 inch per day.

This result was obtained by the aid of the energy-equations which are based on such well-established physical principles that their validity cannot be questioned. These equations contain no arbitrary constants and are therefore free from the highly questionable evaluation that is always necessary when such constants occur.

In developing such equations, sufficient rigor for inspiring confidence in the final numerical results is of course desirable, but at the same time, lucidity, as judged from the standpoint of a person who is not thoroughly accustomed to thermodynamic reasoning, is also desirable, for experience has shown that evaporation, like various other thermodynamic phenomena, involves principles which require great care on the part of both writer and reader if a true understanding is to be communicated.

The equations render all measurement of wind-velocity entirely unnecessary and reduce to negligible proportions the error in the estimate of evaporation which results from unavoidable errors in the measurement of humidity.

The cost of applying the equations must be considered in two aspects: (1) A rough estimate in which low cost is the main consideration and high precision is secondary; (2) the highest possible precision. In both cases the reliability so far as lakes are concerned is greater than has ever been obtained without the aid of the equations, except in those rare instances in which the loss could be estimated directly from gage-heights. In case (1) the cost is trivial since nothing need be done except a small amount of clerical work with the regular Weather Bureau pyrheliometer-readings. In case (2) the cost is about $1,000 for one season and the error is not likely to be greater than ten per cent.

As might be expected, there was a far wider variation from month to month in the lake-loss than in the loss from either pan. This is due to the large amplitude of the lake heat-storage cycle. It should be noted that for an entire season the lake heat-storage becomes negligible.

The Bear Lake investigation--Through the courtesy of the Utah Power and Light Company, observations were made during the summer of 1937 for procuring the data required in estimating the evaporation from Bear Lake in Utah and Idaho by the aid of the energy-equations. A thermally insulated pan was placed near the shore of the Lake and certain observations were made on this pan and on the Lake. On the basis of these observations, the average daily evaporation from the Lake for the months of July, August, and September were computed. A nearby Weather Bureau pan rendered possible a comparison between this instrument and the insulated pan and the Lake.

This is the first time that any pan has ever been compared with a reliable estimate of evaporation from any large deep lake. We have on record a few rare cases such as Stonyford and Elsinore, in which the change of level due to inflow and outflow could be neglected or accounted for, but seldom if ever has this been possible with any but small or shallow lakes. Even in these cases it has seldom been possible to continue any comparison for as much as one whole season.

For an outline of the computations, see Appendix A. Table 1 is a summary of the results.

Table 1--Summary of results

Item	Date, 1937			Seasonal
	July	Aug.	Sep.	average
(1) Number of days in interval	29	31	30	90
(2) Lake-evaporation, inches depth per day	0.154	0.364	0.1895	0.23
(3) Weather-Bureau pan	0.248	0.254	0.169	0.22
(4) Ratio [Lake/(W.-B. pan)]	0.621	1.435	1.12	1.04
(5) Insulated pan, inches	0.279	0.278	0.179	0.24

After a brief historical review, the physical principles on which the computation is based will be explained.

Historical review--A great many evaporation-investigations are based on certain ideas that have probably grown out of suggestions made by John Dalton. This is a little unfortunate as can readily be seen when we remember that although Dalton made some very important contributions to atomic theory and to our understanding of partial pressures, he suffered a serious disadvantage in respect to evaporation because most of the quantitative principles involved in the process were discovered or first clearly recognized after his death, which occurred in 1844. Some of his studies were published in 1802 [see Mem. Manchester Lit., Phil. Soc., v. 5, pp. 535-602].

The principles that have been formulated or discovered since Dalton's death, and which bear on evaporation from lakes, enable us to express in quantitative form the essential facts relative to the conservation of mass and energy and their transport through the air-water interface.

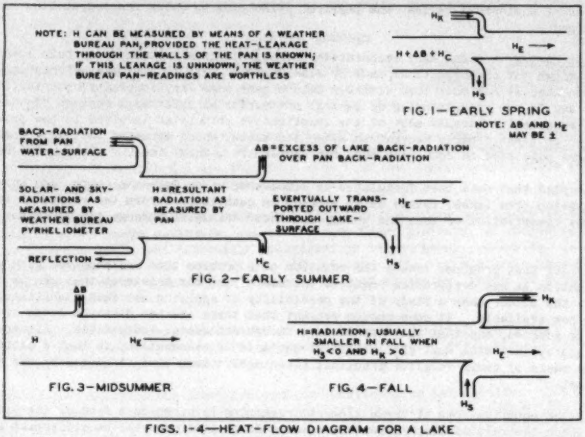
In the belief that progress toward the solution of a problem that has received such a vast amount of attention as has evaporation requires the use of all the knowledge that can be brought to bear on it, the author made a study of the possibility of applying all such quantitative principles as are now available. It soon became evident that there are two distinct lines of reasoning that can be adopted, and that they are almost, though not quite, independent. Either one, if used with appropriate data must give a correct estimate of evaporation, so that a choice must be made on the basis of their relative practical advantages. Each line of reasoning has more than one variant.

The diffusion-equation--One of these lines of reasoning is based on a form of the diffusion-equation, in which the rate of evaporation is regarded as proportional to the difference in vapor-pressure at two different levels in the atmosphere. The proportionality-factor is a function of the wind-gradient and the roughness of the surface. Although this mode of attack is beset with many very serious difficulties, it is nevertheless being used with considerable skill by a very few investigators. Among the most recent publications embodying this idea is the one on transpiration by Thornthwaite and Holzman [see 4 of "References" at end of paper]. It has also been used by Sverdrup [6] and is particularly adapted to ocean-studies.

The energy-point of view--The second line of reasoning, which has been used by Schmidt [7], is based on the principle of the conservation of energy, and has always appealed to the author as being far easier to apply, especially to a lake. As will presently be seen, it requires the determination of certain temperatures which are easier to measure in the case of a lake than in the case of vegetation or soil. The relative advantages of the two points of view with respect to vegetation and soil have not yet been experimentally determined, but there is much in favor of the energy point of view. It may be illustrated by Figures 1 to 4, each of which represents a flow of energy during an interval of time which is assumed to be specified in any particular case. H_I represents that part of the solar and sky radiation which penetrates the lake-surface and H_B represents the net radiation returned by the lake to the sky, but H_I and H_B for the lake are not shown specifically in the diagrams, although their resultant, H, is shown. In some applications we may disregard reflected energy, but in no case should it be confused with H_B which is physically quite different from reflection, and which has been called the effective back-radiation. The reasons for letting $H = H_I - H_B$ will appear presently. It should be understood that all energy-quantities are reduced to a unit-area basis.

As the air moves over the water-surface, if it is warmer it must contribute a certain amount of heat to the water. On the other hand, if the air is cooler it must carry a certain amount of heat away in addition to the latent heat of the evaporated water. This quantity of heat conveyed to or from the water by the air is called convection and is represented by H_K. It has a positive algebraic sign when the heat leaves the water as shown in Figure 4, and a negative sign when heat enters the water as shown in Figure 1. It is likely to be zero in summer as shown in Figures 2 and 3. If the average temperature of the entire water-mass is higher at the end of the time-interval than at the beginning, then a certain amount of heat must have accumulated in the water during the interval, and H_S represents this heat when reduced to a unit-area basis. It becomes negative when the water cools during the interval. This is the condition shown in Figure 4; heat is being supplied by the water for evaporation.

The quantity H_C includes certain components which are usually small. These will be enumerated when H_C is discussed under the heading of relative magnitudes. It will become clear that in most cases we may neglect H_C entirely. In Figure 3, $H_K = H_S = H_C = 0$.


NOTE: H CAN BE MEASURED BY MEANS OF A WEATHER BUREAU PAN, PROVIDED THE HEAT-LEAKAGE THROUGH THE WALLS OF THE PAN IS KNOWN; IF THIS LEAKAGE IS UNKNOWN, THE WEATHER BUREAU PAN-READINGS ARE WORTHLESS
H_K
H_E
$H+\Delta B+H_C$
H_S
FIG. 1—EARLY SPRING
NOTE: ΔB AND H_E MAY BE ±
BACK-RADIATION FROM PAN WATER-SURFACE
ΔB=EXCESS OF LAKE BACK-RADIATION OVER PAN BACK-RADIATION
SOLAR- AND SKY-RADIATIONS AS MEASURED BY WEATHER BUREAU PYRHELIOMETER
H=RESULTANT RADIATION AS MEASURED BY PAN
EVENTUALLY TRANSPORTED OUTWARD THROUGH LAKE-SURFACE
H_E
REFLECTION
H_C
H_S
FIG. 2—EARLY SUMMER
ΔB
H
H_E
FIG. 3—MIDSUMMER
H_K
H=RADIATION, USUALLY SMALLER IN FALL WHEN $H_S<0$ AND $H_K>0$
H_E
H_S
FIG. 4—FALL

FIGS. 1-4—HEAT-FLOW DIAGRAM FOR A LAKE

Now, it is a well-established fact that whenever any substance changes from the liquid state to the vapor-state, a certain amount of heat is required, even when there is no change of temperature. In the present case, H_E represents the quantity of heat which leaves the water in this manner. On those rare occasions when water condenses directly from the atmosphere on to the water-surface, H_E is negative.

If H_E is added to H_B, H_K, H_S, and H_C, each taken with its proper algebraic sign, the result must be H_I. If this were not so, energy would be either created or destroyed in connection with the evaporation-process, and all our experience leads us to believe that such a thing never occurs. If it did, a perpetual-motion machine could be made.

These considerations lead us to the following equation, which is the basis of the present study, but which represents a form of a broad truth that is far more general than the phenomena of evaporation.

$$H_I = (H_B + H_K + H_S + H_C + H_E) \qquad (1)$$

It will be observed that equation (1) contains no symbol representing wind, and some persons have been inclined to regard this as a sure sign that something is wrong with the reasoning. A careful consideration of the facts, however, will show that the equation is correct. There can of course be no doubt that evaporation is related to wind, and if we desire to take account of this fact in an explicit way, we can do so by adopting the type of reasoning based entirely on the diffusion-process. But when we avail ourselves of the advantages of the energy-concept, we need pay no attention to wind in any direct way, although it is automatically taken care of indirectly.

If this seems abstract, or uncanny, the reader should remember that anyone who wants to deal effectively with natural phenomena must accustom himself to abstractions. To paraphrase the language of a most competent geophysicist, the reader should not blame the equations, he should blame the lake. Every pound of water that evaporates at ordinary temperature must take away 1,060 btu with it, so that if we can use equation (1) to find the number of btu that leave every square foot of the lake by evaporation in a given time, we can divide by 1,060 to obtain the number of pounds per square foot; and dividing further by 62.2, which is the number of pounds per cubic foot of water, must give us the depth of loss in feet. It may help if one recognizes that the temperature of the evaporating surface will always adjust itself so as to make results obtained by a correct application of the diffusion-equation consistent with those obtained from equation (1).

A second criticism that has been raised against this point of view is that it is correct in theory but will never work in practice because when we attempt to determine the thermally convective component H_K we are immediately plunged into all the difficulties that confronted us in determining evaporation in the first place. In other words, it appears just as difficult to estimate the amount of heat brought to the lake by the wind as it is to estimate the amount of moisture carried away.

It must be freely admitted that on the basis of purely superficial considerations this objection appears to have considerable force. A careful examination of the matter shows, however, that certain physical principles can be introduced in such a way as to eliminate this trouble entirely. We can adopt the simple expedient of making the imperfectly understood quantities involved in the transport of heat cancel those involved in the transport of moisture, and can thus arrive at an equation that is capable of a definite application. The derivation of a certain auxiliary equation by Bowen [2] was an important step in this, but its practical success depends on fortunate circumstances respecting the relative magnitudes of the various terms in equation (1). These will be considered after Bowen's equation has been discussed more fully.

Reduction of fundamental idea to form suitable for computation of evaporation--In order to accomplish the cancellation just mentioned, we introduce a quantity R, which has come to be known as Bowen's ratio, although so far as the author knows Anders Ångström was the first person to use it.

We may define Bowen's ratio by the equation

$$H_K = H_E R \text{ or } R = (H_K/H_E) \tag{2}$$

This means that R is the ratio of the atmospheric component, or heat carried away by thermal convection, to the heat carried off by the vapor, that is, by mass-transfer. If in equation (1) we substitute the value of H_K given by equation (2), we obtain

$$H_I = (H_B + H_E R + H_S + H_C + H_E)$$

which readily gives

$$(H_I - H_B) = [H_E(1 + R) + H_S + H_C] \tag{3}$$

Bowen showed that when R is defined by equation (2), it can be computed by the following equation

$$R = 0.46\ [(t_1 - t_2)/(p_1 - p_2)]\ (P/760) \tag{4}$$

in which the t's represent temperatures in Centigrade and the p's represent vapor-pressures in mm of mercury. The subscript 1 refers to the water-surface, while the subscript 2 refers to the air. Thus t_1 is the temperature of the water-surface, while t_2 is the temperature of the air; p_1 is the vapor-pressure of saturated vapor at the temperature of the water-surface, while p_2 is the partial pressure of whatever amount of water-vapor may happen to be in the air. P is the barometric pressure expressed in mm of mercury. When temperatures and pressures are expressed in Fahrenheit and inches, the coefficient becomes 0.010.

The general reasonableness of Bowen's equation is at once apparent because the quantity of heat brought to the water by the moving air is certainly proportional to the excess of air-temperature over water-surface temperature, and the amount of moisture carried away undoubtedly increases with the excess of the saturated vapor-pressure at the temperature of the water-surface over the partial pressure of the moisture in the air. These general relations must hold regardless of the velocity or character of the air-movement. That the equation is applicable in the precise form and with the coefficient given by Bowen is not evident without analysis, but after carefully reading Bowen's commendable treatment and investigating the effect of turbulence on the transport of heat and moisture the present author feels confident that the equation is correct at least to a very close approximation. Any reader who is in doubt should consult Bowen's paper as well as the report of the experimental verification. See Cummings and Richardson [3] and Arnold [1].

One of the great advantages of the energy point of view lies in this elimination of the need for concerning ourselves about the velocity and character of the air-movement.

Relative magnitudes--Long experience has shown that of all the quantities involved in

equation (1), the incoming radiation, H_I, is by far the largest, and this greatly simplifies the practical application. The method of dealing with H_I and the effective back-radiation, H_B, will be explained in the following section which deals with the measurement of radiation. The thermally convective component, H_K, is positive during some parts of the day and negative during other parts. During a 24-hour interval the positive and negative values cancel each other almost completely.

The measurement of the heat-storage, H_S, involves no serious difficulty although it may be expensive when very high accuracy for short intervals of time is desired. We merely need to know the area and temperature of the lake at various levels. When the time-interval is an entire summer season, H_S may be regarded as zero. It is a little like H_K in this respect, except that the cancellation occurs in connection with a seasonal instead of a daily cycle.

It should be remembered that the equation applies to any body of water from a small pan-full to a large lake. In the case of the pan, there may be an appreciable leakage through the walls, although with thermal insulation this can be made negligible. The quantity H_C is intended to include such leakage, and for a lake it is always negligible. Also, there is water being added to a pan to make up for the evaporation, and water usually runs into and out of a lake. This water carries some heat with it, which is also included in H_C. Owing to thermal expansion, there may be an apparent evaporation, either positive or negative, which is likewise included. In almost all cases, we may regard the total of all components of H_C as zero, although corrections are easily applied when necessary.

Measurement of incoming and outgoing radiation--For years past, the United States Weather Bureau has been maintaining an increasing number of recording pyrheliometers located at selected points in the continental United States and its territorial possessions. The type of instrument used consists of a thermopile connected to a recording microammeter. The hot junctions of the thermopile are in close contact with a black ring, while the cold ones are in similar contact with a white ring. The rings are inclosed in an evacuated bulb, and exposed horizontally to the radiation from the Sun and Sky. The readings of the ammeter, after proper calibration, are regarded as a measure of the intensity of the radiation. The chief disadvantage of this instrument for measuring evaporation is that it gives us no information about radiosity, which is the sum of the effective back-radiation, H_B, and the reflection-part of the incident energy, but, as will presently appear, this is not as serious as it might at first seem (see Appendix B).

In most of the applications of the energy-equations that have thus far been made, the quantity $(H_I - H_B) = H$ has been measured by the aid of a thermally insulated pan. The area should not be less than four square feet and the depth not less than eight inches. One method of using it is set forth in the explanation of the Bear Lake computations given in Appendix A. In addition to its relative cheapness, the pan requires no calibration, so that it is itself a primary instrument--a matter of considerable importance.

Some preliminary experiments with a photoelectric method of measuring resultant radiation have been made and seem to indicate interesting possibilities [see Trans. Amer. Geophys. Union, 1935, pp. 515-519].

There seems to be no difficulty in keeping the radiation error below two per cent when a thermally insulated pan is used.

Computation of evaporation--Having measured the radiation, we may solve equation (3) for H_E, and by dividing by L obtain the evaporation in pounds per square foot of open-water surface, denoted by E. Thus

$$E = (H_I - H_B - H_S - H_C)/L(1 + \bar{R}) \qquad (5)$$

We may substitute the radiation as measured by the pan for the quantity $(H_I - H_B)$ in equation (5), with the understanding that H_S is now the change in heat-content of the lake occurring during the time-interval under consideration, and $\bar{R}$ is the average value of the lake R for the same time-interval. The latent heat of water is denoted by L. Its magnitude is 1060 btu per pound at ordinary temperature. The way in which this substitution was made using the Bear Lake data is explained in Appendix A.

Costs--At the present time, our knowledge of the magnitudes of the various quantities involved in the evaporation-process is so incomplete that any expenditure of funds, however large or however small, can be justified only on the basis of research and development, with greater knowledge of these magnitudes as the objective.

By applying the energy-concept in a way presently to be described, an engineer can very easily obtain a rough estimate of the seasonal loss from a lake, without incurring any expense for the operation of any pan, or any other instrument; but if he needs an actual measurement, with an estimate of his error, he must be prepared to carry out an expensive program. Any person who understands elementary principles can very easily make the rough estimate in the following manner.

If he merely looks up the pyrheliometer-readings as reported in the Monthly Weather Review for two or three stations nearest the point in which he is interested, multiplies these readings by 3.7 to reduce from calories per square centimeter to btu per square foot and subtracts 200, he will have a fair estimate of the energy that leaves the lake as latent heat. The result will depend, of course, on the stations chosen and on the time covered, but at such widely separated points as Elsinore in the south and Stonyford in the north of California, Fort Collins in Colorado, Lifton and Twin Falls in Idaho, and Madison in Wisconsin, there is known to be enough uniformity to enable us to say beforehand that the incoming radiation will be in the vicinity of 1,500 btu per square foot per day in the summertime, giving about 1,300 as the amount of energy available for evaporation. This corresponds to about 1.3 pounds per square foot, or about 0.02 foot of depth.

The two places which depart most widely from the value here assumed are Stonyford and Fort Collins, the former being higher and the latter being lower. At the former place, data are available for one month only, while at the latter there was no real lake but only a reservoir 85 feet in diameter and seven feet deep. Even at these places, however, the departure does not exceed the liberal tolerance that seems to have been established in the literature of evaporation.

It should be explained that the data at Elsinore, Fort Collins, and Stonyford consist of actual observations on change of lake- or reservoir-level, while at Twin Falls, which has about the same climate as Lifton, the Weather Bureau pyrheliometer-readings are referred to. Fortunately, such data were available for the same period as that covered by the observations at Lifton which have been used in this paper. At Madison, pyrheliometer-readings have been made since 1911.

An unpublished comparison of a summary of the Madison radiation-data with a corresponding summary of the energy-components for nearby Lake Mendota makes it necessary to assume 0.35 as the average value of R. This comparison was made by Juday on an annual basis, and the evaporation-data were not obtained by direct observations on the Lake but were inferred from pan-readings made between 1906 and 1911. Juday did not actually assign any value to R, but the value here mentioned would make his components balance.

Now, it is a very significant fact that there is no stage of precision between the rough estimate obtained by the method just outlined and something that involves the essentials of the complete program carried through at Bear Lake unless we can find some inexpensive and fairly accurate way of applying the diffusion-equation. At the present time, the difficulties in the way of even a moderately accurate, and at the same time inexpensive, application of the diffusion-equation appear to be so extremely serious as to render this procedure commercially inadmissible, at least for a long time to come.

At present, therefore, we must choose between no cost at all and a cost of about $1,000, including observations and computing.

However, if this expensive program can once be carried out for four or five lakes, there is considerable likelihood that we shall thereby be placed in an advantageous position for evolving a procedure which will yield a much higher precision than the rough use of the pyrheliometer-data just outlined and which can still be done at a nominal cost.

For example, we know that for a lake H_C is frequently negligible and for a season H_S is negligible for either lake or pan. If then R were the same for a pan as for a lake, an insulated pan would necessarily have the same depth of loss as a lake except when H_C must be taken into account. As a matter of fact, the R's are not quite the same, but they do not, in the light of our present knowledge, appear to differ by enough to make the discrepancy between pan and lake greater than about 20 per cent. The pan is likely to be the greater for a whole season. If then we adopt a coefficient of 90 per cent for the insulated pan, we may be very close to the truth in a great majority of the cases.

There is, however, no way of knowing matters of this kind without actually measuring the lake-evaporation in a large enough number of cases to permit generalizing. And the energy-equations give us the only practical means of doing this.

We do not escape the need for this expensive calibration against lakes by merely choosing a different type of pan. Thus, it is quite possible that the Weather Bureau pan acts as if it were insulated and, if so, then all that was said about the insulated pan applies with equal force to the Weather Bureau Pan. If the latter pan does not act as if it were insulated, then matters are obviously worse for it than for the insulated pan.

It is true that we have the calibration of the Weather Bureau pan [5] made at Fort Collins, but we have no means of appraising it until we obtain rather complete information regarding the leakage through the walls. The thoroughness with which the observations and computations relating to the Fort Collins experiment were carried out justifies the conclusion that the calibration will have great value if the heat-leakage through the walls turns out to be small. It is, nevertheless, only a single calibration, and in view of its yielding a coefficient of 70 per cent, while the Bear Lake run yielded 104 per cent, there certainly is need for further investigation before any generalization can be drawn.

Meanwhile, from the standpoint of accuracy or reliability, the Weather Bureau pan has no advantage over the rough estimate based on pyrheliometer-readings. This must be evident from the observed fact that the range of variation in the different estimates of the pan-coefficient is about equal to the range of variation of the true seasonal lake-evaporation at widely separated places.

This remarkable stability of the phenomenon of lake-evaporation at widely separated places proves conclusively that the Weather Bureau pan needs more scientific investigation than it has thus far received. Until its physical characteristics are more clearly understood, it cannot add anything to our knowledge of the losses from lakes, from vegetation, or from soil that we have not already gained by direct observation on such bodies.

Acknowledgments--The writer has not only had the generous cooperation of the Utah Power and Light Company in procuring the data used in this paper but, in formulating the presentation of the material, he has been influenced by such a large number of persons that he is somewhat reluctant to regard himself as the individual author. While the task has been difficult, it is hoped that at last the energy point of view has been stated in a manner which is not only valid from a physical standpoint, but is also acceptable from the standpoint of most persons interested in evaporation.

The present form of the paper is in large measure the outcome of several conferences with Brooks Morris, acting under the direction of Professor R. T. Knapp of the California Institute of Technology and the Soil Conservation Service, although Professor Franklin Thomas of the California Institute offered many valuable suggestions.

The writer has, however, been influenced in large measure by conferences with Dr. H. U. Sverdrup, Director, and Dr. G. F. McEwen, Professor of Physical Oceanography of the Scripps Institution, and by Professor S. T. Harding of the Department of Irrigation of the University of California, as well as by Professor L. M. K. Boelter of the Department of Mechanical Engineering and Professor Joseph Kittredge of the Division of Forestry.

Jarrett Oliver of the United States Geological Survey has offered many helpful suggestions, as has also Dr. L. A. Richards and his associates in the Bureau of Plant Industry at Riverside.

Through the kindness of Professor Chancey Juday of the University of Wisconsin, it has been possible to use certain unpublished data relative to Lake Mendota.

The sympathetic attitude of Dr. Nicholas Ricciardi, President of the San Bernardino Valley Junior College, where the computing was done, has been most helpful.

A grant from Sigma Xi aided in meeting various expenses.

The writer is grateful to the various individuals and organizations consulted in connection with the Work Projects Administration project for the endorsements that made the project possible, and to the former local administrators for their cooperation.

Appendix A--Bear Lake computations

The insulated pan was two feet square and eight inches deep. The water-surface was maintained an inch below the rim, making a water-depth of seven inches. A regular series of observations was made every two hours. These included the amount of water required to make up for the

Table 2--Averages for Bear Lake, July to September, 1937

Value	Morning at hour					Afternoon at hour				
	4	6	8	10	12	2	4	6	8	12
Month of July										
R for pan	+0.23	+0.17	-0.24	-0.09	+0.05	+0.09	+0.10	+0.12	+0.18	+0.18
R for Lake	+0.30	+0.29	+0.13	+0.02	-0.05	-0.13	-0.15	-0.16	+0.12	+0.23
Body-temp., °F	58.8	57.9	60.8	68.0	77.9	84.4	86.0	82.4	74.5	65.3
Pan-surf. temp., °F	58.6	57.7	61.0	68.4	77.7	84.4	86.0	82.4	74.8	65.5
Lake-surf. temp., °F	66.2	67.5	68.5	71.1	73.9	75.9	76.3	75.2	71.6	69.3
Dry bulb, °F	54.5	55.8	63.5	70.3	74.7	77.7	78.3	73.9	66.0	58.8
Make-up, Btu/ft^2	172.3	60.9	54.6	62.5	70.1	132.0	206.0	288.2	238.4	233.8
Month of August										
R for pan	+0.27	+0.24	-0.37	-0.32	-0.09	+0.01	+0.03	+0.05	+0.13	+0.16
R for Lake	+0.35	+0.36	+0.21	+0.05	-0.10	-0.12	-0.09	-0.02	+0.15	+0.24
Body-temp., °F	56.3	53.2	54.0	61.3	72.7	80.8	82.6	79.9	73.4	64.6
Pan-surf. temp., °F	55.6	53.2	55.0	63.0	73.4	81.1	82.8	79.9	73.2	63.7
Lake-surf. temp., °F	69.4	68.5	68.9	70.9	73.2	75.0	75.7	75.4	73.8	72.1
Dry bulb, °F	50.9	49.5	59.2	68.5	75.7	79.9	79.5	75.9	65.5	57.7
Make-up, Btu/ft^2	176.4	80.5	36.9	42.5	80.8	144.2	221.6	282.3	206.0	239.0
Month of September										
R for pan	+0.22	+0.24	-0.41	-0.29	-0.16	+0.02	+0.05	+0.10	+0.19	+0.21
R for Lake	+0.36	+0.41	+0.29	+0.07	0.00	-0.04	-0.06	+0.05	+0.22	+0.32
Body-temp., °F	50.9	48.0	48.6	55.6	63.7	71.6	72.9	69.8	64.2	56.5
Pan-surf. temp., °F	50.5	47.8	48.7	57.0	64.2	71.4	72.9	69.6	64.0	56.5
Lake-surf. temp., °F	63.3	62.2	62.8	64.2	67.6	68.7	68.4	67.3	66.4	64.9
Dry bulb, °F	46.0	43.9	51.8	61.5	67.6	70.2	70.3	65.5	57.2	50.9
Make-up, Btu/ft^2	108.0	64.6	42.7	34.0	54.5	102.5	177.0	160.3	96.2	126.4

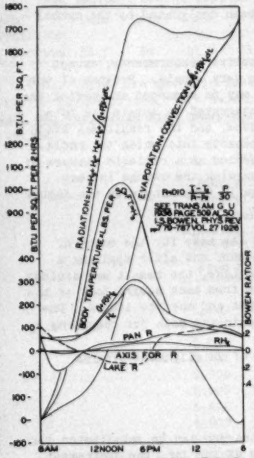


FIG. 5—COMPUTATION OF RADIATION AT LIFTON, IDAHO, JULY 2-31, 1937

evaporation-loss from the pan, the temperature of the surface of the water in the pan, and the average temperature of the total mass of water in the pan. Wet- and dry-bulb readings were taken, and the temperature of the Lake-surface was measured.

About every ten days, a series of subsurface temperatures in the Lake was obtained. These were used in connection with the known relation between area and depth for the purpose of computing H_S.

The computing was done as a Work Projects Administration project.

Computation of H from pan-data--The make-up water was measured in cubic centimeters, but was reduced to pounds. The temperatures were all either measured in Fahrenheit or reduced to that scale. Dividing the pounds of water by the pan-area gave the pounds per square foot, and multiplying by the latent heat gave H_E in btu per square foot. This was done for each time-interval of an average day and the results were plotted. The data for the average day were obtained in the following manner:

The make-up water for a certain interval, say 8 to 10 o'clock for all the days in July, was averaged. The values for the next time-interval, 10 to 12, were likewise averaged, and so on throughout the 24 hours. A similar computation was carried out for the other measurements and for the other months. These averages are presented in Table 2.

In Figure 5, the computations are presented in graphical form for the month of July. The curve representing the diurnal variation of make-up btu's per square foot was

Table 3--Steps in computation

Value	Month					
	July		August		September	
	Cal/cm^2	Btu/ft^2	Cal/cm^2	Btu/ft^2	Cal/cm^2	Btu/ft^2
(1) Rad'n as measured by pan = H	475	1760	439	1620	278	1030
(2) ΔB	24	89	23	85	40	148
(3) Corrected rad'n	451	1670	416	1540	238	882
(4) Average daily warming = H_S	228	845	-124	-459	-65	-241
(5) $(H - H_S)$	223	826	540	2000	303	1020
(6) $(1 + \overline{R})$	0.97		0.99		1.07	
(7) Evap'n, inches	0.156		0.364		0.19	

Notes: $(1 + \overline{R})$ is defined by the equation $\int LE(1 + R)dt = (1 + \overline{R})\int LEdt$, where $\int LEdt$ is the evaporation in Btu per square foot; ΔB is the difference in back-radiation from pan and Lake.

An evaluation of $\overline{R}$ which is well within a tolerance of ten per cent is possible by virtue of the following conditions: (1) There is never any warming of the Lake during the night; (2) the daytime warming-rate never exceeds the resultant radiation-rate; (3) R varies between narrow limits.

These facts enable us to draw maximum and minimum curves for the diurnal march of Lake-evaporation, with the certain knowledge that the true curve lies between and that the limiting curves are sufficiently close together to keep the true curve from differing from either of them by more than ten per cent. In this way we avoid the necessity of making detailed measurements of Lake subsurface-temperatures. The curves here referred to are not shown in Figure 5.

designated as H_E. The curve for R was then plotted and multiplied graphically by H_E. This gave the H_ER or H_K curve, which in turn was added graphically to the H_E curve to obtain a curve showing the diurnal change of the total transport of heat through the surface by the combined processes of evaporation and convection. The curve so obtained has been designated by the symbol $(1 + R)H_E$.

As already pointed out, only two hours elapsed between consecutive measurements, except during the latter part of the night when changes were taking place very slowly. Because of the shortness of this interval, the total transport-curve, $(1 + R)H_E$, may be regarded as showing the rate of transport as a function of time. It can accordingly be integrated to obtain the total transport throughout the 24-hour interval. This integration was done, and the result was added to the warming curve to obtain the sum of all three important components into which the radiation penetrating the surface was divided. This latter sum was regarded as a reliable measure of $(H_I - H_B) = H$ for July. By the warming curve is meant the curve showing the change in heat-content of the pan-water. It is obtained by multiplying the change in temperature by the number of pounds of water under each square foot of open water-surface.

Computation of lake-evaporation--The average daily warming of the Lake for the month of July was then subtracted from the radiation, H, as measured by the pan, and after applying a very small correction, ΔB, for the difference in H_B for the pan and Lake, the result was divided by $[1060 \times (1 + \overline{R})]$ for the Lake to obtain the pounds of water lost from each square foot of the Lake, in accordance with equation (5). This was then reduced to feet and then to inches. The steps in the computation are shown in Table 3. Tables 4 and 5 contain the data for computing H_S.

The labor of computing the R's was greatly reduced by the use of an alignment-diagram described in the Monthly Weather Review [v. 58, pp. 142-144].

Appendix B

Experience has shown that at night a one-gallon vacuum insulated jar can be substituted for the pan, and if the water is kept four or five inches below the rim of the jar, the instrument gives a good measure of back-radiation to the sky without any attention during the night. Under these conditions, the evaporation is so small that H_ER becomes negligible, so that the change in weight of the water in the jar, together with the change in body-temperature, is adequate for the computation of back-radiation with sufficient precision for estimates of evaporation from

Table 4--Temperatures at Bear Lake, July to October, 1937, by Utah Power and Light Company

Month-day	7-2	7-9	7-17	7-23	7-30[e]	8-6	8-16	8-21	9-2	9-11	9-18	9-25	10-1
Time	12 noon	11 am	10 am	9:30 am	11:15 am	9:30 am	9:15 am	9:00 am	11:20 am	9:15 am	8:45 am	11:00 am	9:45 am
Bottom[a] Temp., °F	107	108	105	150+	110	115	125	130	125	120	120	127	120
Air	78	75	76	74	77	66	69	64	78	64	59	50	61
Depth[a], 0	69	69	69	69	73	68	69.5	69	67	65	65	61	60
5	67.5	68	66	69	70	68	69	69	66	65	65	61	59.5
10	63	64	65	69	70	68	69	69	66	65	65	61	59.5
15	61	63	65	69	70	68	69	68	66	65	65	61	59.5
20	60.5	61.5	65	68	70	68	69	68	66	65	65	61	59.5
25	59.5	60	64.5	66.5	69	68	69	68	65.5	65	65	61	59.5
30	58.5	59	59.5	65	69	68	69	68	65.5	65	65	61	59.5
35	56.5	56	55	59	69	67.5	69	68	65.5	65	65	61	59.5
40	55.5	55	52	55	69	62	62.5	64	65.5	65	65	55	59.5
45	53	52	50	53	62	55	58	57	60.5	63	65	50	59.5
50	51	50	49	51	56	52.5	54	51.5	51.5	51	64.5	47.5	59.5
55	49.5	48	46	48.5	54	50.5	51	48.5	49	48.5	56.5	45.5	59.5
60	48.5	46	45.5	47	52.5	49	49	46.5	48	46	52.5	44.5	59.5
65	48	45	44.5	46.5	51	47	47.5	46	45	44.5	50	44.5	....
70	47	44.5	44.5	45.5	50	45	45	45	44.5	43.5	47	44	49
75	46	44	43	44	49	44.5	43.5	45	43	43	46	43.5	47
80	45	43	41	43.5	48.5	43	42.5	44.5	42	42	44.5	43.5	46
85	43.5	42	41	42.5	47	43	42	43.5	41	41	42.5	43.5	....
90	42	41	41	41.5	45.5	42.5	41.5	42.5	41	41	42	42.5	43.5
95	41	40.5	40.5	41	44.5	41.5	41.5	42	41	41	41.5	42	43
100	40.5	40.5	40.5	40.5	43.5	41	41	41	40.5	40.5	41.5	42	42.5
Notes													
Weather[b]	P cl	P cl	P cl	P cl	P cl	Cl	P cl	P cl	P cl	C	P cl	P cl	C
Wind[c]	Calm	Calm	Calm	N br	Calm	Calm	NW br	NW	Calm	Calm	NW br	Calm	Calm
Condition surface	Sl r	Sm	Sl r	Sl r	Sl r	Sl r	Sl r	Ro	Calm	Sl r	R	Sm	Sl r

[a] All depths are given in feet. [b] P cl = partly cloudy, C = clear, Cl = cloudy. [c] br = breeze. [d] Sl r = slight ripple, Sm = smooth, R = ripple, Ro = rough. [e] Night preceding reading of July 30, 1937, was very rough with heavy southwest wind; it is believed this day's readings were taken over a spring.

Table 5--Storage-capacity, Bear Lake

(Pump-seal, elevation 5,900 feet; limit of operation of pumps, elevation 5903-02 feet; maximum storage-level, elevation 5923.65 feet)

Elevation		Storage-capacity	Elevation		Storage-capacity
From	To		From	To	
ft	ft	acre-ft	ft	ft	acre-ft
5,900	5,901	52,218	5,913	5,914	66,429
5,901	5,902	58,711	5,914	5,915	67,017
5,902	5,903	59,235	5,915	5,916	67,632
5,903	5,904	59,838	5,916	5,917	68,306
5,904	5,905	60,459	5,917	5,918	68,906
5,905	5,906	61,152	5,918	5,919	69,376
5,906	5,907	61,887	5,919	5,920	69,728
5,907	5,908	62,576	5,920	5,921	69,971
5,908	5,909	63,261	5,921	5,922	70,144
5,909	5,910	63,882	5,922	5,923	70,341
5,910	5,911	64,448	5,923	5,924	70,565
5,911	5,912	65,050	5,924	5,925	70,717
5,912	5,913	65,737			

lakes. We may thus obtain H_B for use in equation (5), when the pyrheliometer is employed for obtaining H_I.

When the pyrheliometer is used, however, there is no simple way of correcting for the energy reflected from the water-surface. This probably amounts to about ten per cent of H_I.

References

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INFILTRATION-CAPACITY VALUES AS DETERMINED FROM A STUDY OF AN EIGHTEEN-MONTH RECORD AT EDWARDSVILLE, ILLINOIS

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During 1936 and 1937, the hydrologic research-program of the Soil Conservation Service was expanded to include the collection of precipitation and runoff-data from a large number of typical small watersheds at research-centers throughout the country. One of these projects is near Edwardsville, Illinois. It includes three watersheds, respectively known as W-I, W-II, and W-IV, and having areas of 27, 50, and 290 acres, respectively. These watersheds are in their undisturbed natural condition. W-I is entirely in cultivation, while the others include large portions of pasture and woodland (see Fig. 1).

The area is adequately covered by recording rain-gages and the runoff is measured over broad-crested, V-notch weirs equipped with waterstage-recorders. The runoff-studies on the Edwardsville Project are conducted jointly by Research and Technical Operations of the Soil Conservation Service in cooperation with the Illinois State Agricultural Experiment Station. The technical phases of the work are carried out by R. P. Weeber of the Edwardsville Project under the direction of the Hydrologic Division which is represented by Neal E. Minshall, line-project leader for the runoff-studies in Region V. The equipment was put in operation during February and March, 1938, and complete records from that date are available.

Through the courtesy of Dr. M. L. Nichols, Assistant Chief of the Soil Conservation Service in Charge of Research, and C. E. Ramser, Chief of the Hydrologic Division, the junior author, under a graduate fellowship in Hydrology at Washington University, was permitted during 1938-39 to undertake the analyses of the basic data accumulated; during 1939 and 1940, he continued the analytical work also as a Junior Engineer on the research staff of the Soil Conservation Service. During the whole period, the analytical work was under the advisory supervision of the senior author, acting as Consultant to the Office of Research of the Soil Conservation Service.

The immediate objective of this analytical work has been the determination of the actual infiltration-capacity which has existed during each storm-period for each of the watersheds studied. The analytical work was first undertaken for the smaller W-I watershed, for the reasons that the hydrographs from this watershed were somewhat more sharply defined, and the possibility of connecting runoff to actuating precipitation is more favorable. During the course of the work on this watershed, much of the methodology for collecting and tabulating data was becoming standardized for the Soil Conservation Service, and the records from this small watershed were extensively used to test proposed procedure.

All of the precipitation-periods have been studied with respect to Watershed W-I for the

year March, 1938, to March, 1939, and as stated later, the studies have been extended in part through the summer of 1939.

The analysis has also been completed for all of the precipitation-periods for Watershed W-II for the same length of record.

Inasmuch as W-I was entirely in cultivation and W-II very largely in pasture, it was expected that distinctive differences in infiltration-capacity as between these watersheds would be found. In this respect the results were somewhat disappointing. There is comparatively little difference between the infiltration-capacities of these two watersheds. This is probably due to the fact that the cultivation on W-I has been in strips and that the lower strip has been in alfalfa, and that this combination has developed controlling factors approaching in some aspects that of pasture-grass. On the other hand, the pasture-cover for W-II has throughout the period been relatively poor, with considerable areas of weedy and sparse grass. For these reasons, the results do not indicate the differences that might possibly exist between, say, cultivation in row-crops on the one hand, and a good stand of pasture-grass on the other.

The basic data collected give a very complete picture of rainfall-occurrence and of runoff for each precipitation-period throughout the record. The data-collection equipment has apparently been quite satisfactory and has been well managed, and the basic data are unusually accurate and satisfactory to work with.

The data have been reduced to graphical form for each precipitation-period, and in this form show: (a) A diagram of rainfall-intensity; (b) the mass-curve of rainfall; (c) the hydrograph of runoff; and (d) the mass-curve of runoff.

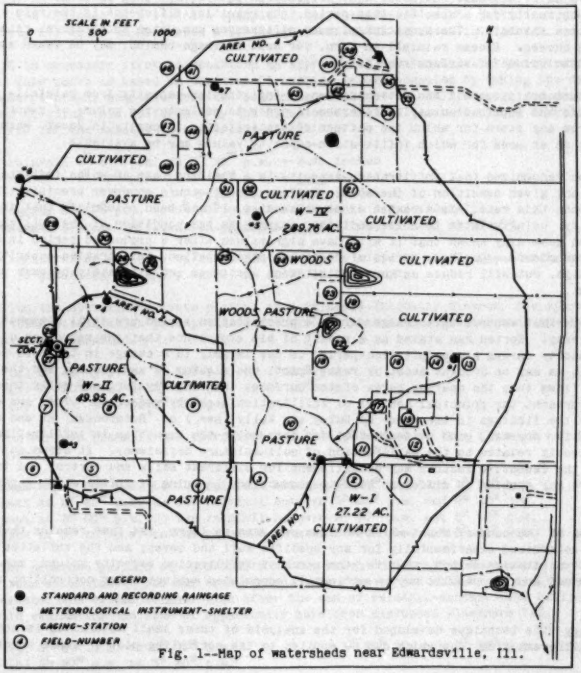


Fig. 1--Map of watersheds near Edwardsville, Ill.

The runoff-data are corrected for pondage behind the weirs, and are representative of inflow into the small ponds above each weir.

As stated above, the objective of the present analysis is the determination of infiltration-capacity values for as much of the precipitation-periods as the data will permit. The ultimate objective of this analysis is to make available such infiltration-capacity values for estimating the flood-flow from other storm-precipitation periods. To the extent that these values become generally available, it will be possible to avoid entirely the older technique in which runoff was estimated by applying a coefficient of runoff to mean precipitation-rate for a chosen duration of rainfall--that is, excess rainfall will be determined by subtracting infiltration-capacity rate during the period of excess rainfall from precipitation-intensity rate. Excess rainfall in turn may be taken as substantially equivalent to mass-runoff and runoff-rates may be determined by an application of the unit-hydrograph or channel-storage methods.

In the past, in the absence of an adequate understanding of the mechanics of infiltration, those factors which control infiltration during and subsequent to a storm-period could not be separately isolated, and infiltration has largely been thought of in terms of monthly, seasonal, and annual values.

The conception of "infiltration-capacity" introduced by Horton and the improved knowledge of the mechanics of infiltration which has appeared out of the research-programs of the Department of Agriculture have completely altered this situation.

As defined by Horton, infiltration-capacity is "the maximum rate at which the soil, when in a given condition, can absorb falling rain." It is a significant physical property of the soil. It is a rate value of the same character as precipitation-intensity. When subtracted from precipitation-intensity for a specific time-period, the resulting difference is the rate of production of excess rainfall. The summation of such differences evaluates total excess rainfall for any period chosen. Excess rainfall in turn, for most drainage-basins, may be taken as sensibly equivalent to volume of surface-runoff.

These relationships permit the determination of infiltration-capacity from rainfall- and runoff-data, and the application may be reversed in order to estimate the volume of runoff or stream-flow from any storm for which the pattern of precipitation-intensity is known, when such a storm occurs on an area for which infiltration-capacity values may be available.

It must be recognized that infiltration-capacity is a limiting rate at which infiltration may occur for any given condition of the soil. Surface-runoff occurs whenever precipitation-intensity exceeds this rate. As a result of other studies, it has been recognized that infiltration-capacity, being related to soil-condition, changes as the condition of the soil changes; and it has been generally known that it will have high values after a prolonged period in which no precipitation occurs. During a period of continued precipitation, infiltration-capacity will be initially high, but will reduce as the precipitation continues and ultimately becomes substantially constant.

The factors that control this change during a precipitation-period are still somewhat a matter of controversy. Horton has stated as a result of his experience that the reduction of infiltration-capacity during a precipitation-period is due largely to a change in the soil-surface structure, such as may be brought about by rain-impact, the closing of sun-checks, and the infiltration of fines into the coarser pores of the surface. Undoubtedly for many soils these changes may represent the principal control of infiltration-capacity reduction. They are well illustrated by the findings in the paper by Duley and Kelly [see 1 of "References" at end of paper]. There is, however, good evidence that for many soils the reduction in infiltration-capacity is closely related to the satisfaction of soil-moisture deficiency. It seems quite probable that the causative factors may be different for different soils and covers, and in any particular case may combine in different ways to produce the lowering of infiltration-capacity values.

Regardless of the causes, about which we have yet much to learn, the fact remains that these values can be determined experimentally for any specific soil and cover; and the variation throughout a precipitation-period, that is, the march of infiltration-capacity values, may be readily determined and the results may be ultimately correlated against other controlling variables.

Methodology--The technique developed for the analysis of these small watersheds is necessarily quite different from that which can be applied to the sprinkling-plot or small runoff-plot,

where the response between the hystogram and the hydrograph is so rapid that such factors as retention, opportunity, and infiltration-capacity are more readily determined. Had there been one or more small runoff-plots within each of the watersheds at Edwardsville, the process of analyzing the watershed-data would have been much simplified. The analysis of the plots could have been carried out for each storm before the analysis of the watershed as a whole was undertaken. The simpler and more specific analysis of the plots would provide immediate knowledge of infiltration-capacity, retention, and general overland flow-characteristics, which would have been invaluable in expediting and simplifying the watershed-analysis.

It has been found that the hydrograph reflects the general characteristics of the hystogram with a rather marked degree of sensitivity. This is not so surprising in the case of the small drainage-basins with their comparatively short time of concentration and comparative freedom from very definite influences of channel-storage. This feature is conducive to a rather precise determination of infiltration-capacities. By correlating a definite period of excess rainfall with the quantity of runoff that is represented by the area beneath that portion of the hydrograph which can be rather definitely attributed to this mass of excess rainfall, the infiltration-capacities can be computed at various points throughout the entire period of opportunity, or for separate periods. In this manner it is possible to determine the variations in infiltration-capacities throughout any one rainfall-period in any storm that produced two or more hydrograph-peaks.

The method of approach in the analysis of the hydrograp having two or more peaks is itemized in the following paragraphs:

The various stages involved in the analytical procedure are first stated in as general terms as possible, so as to be applicable to all hydrographs of the multi-peak type. The general statements are then followed by a specific example of the application of the particular step to the storm of July 17, 1938, on Watershed W-I, the graph of which is shown in Figure 2.

(1) It is necessary first to establish an approximate working curve of infiltration-capacity. This curve is based on the overall average value, computed by taking the difference between mass-rainfall, measured from the beginning to end of rainfall-excess, and mass surface-runoff, and dividing this difference by the duration of rainfall-excess plus a fraction of the time required for the exhaustion of surface-detention.

Mass-rainfall $0^h\ 47^m$ p.m. to $3^h\ 30^m$ p.m. = 3.45 inches
Mass-runoff $1^h\ 03^m$ p.m. to $6^h\ 00^m$ p.m. = 1.58 inches
Total loss = 1.87 inches
Opportunity $0^h\ 47^m$ p.m. to $3^h\ 30^m$ p.m. = 2-3/4 hours (approximately)
Approximate average infiltration-capacity = 0.68 inch per hour at $2^h\ 10^m$

This infiltration-capacity value is plotted at the midpoint of the opportunity-period, and through it is passed an arbitrary curve, as shown on the graph.

(2) With the approximate curve plotted on a rainfall-intensity diagram, the approximate periods of time within which precipitation occurred at intensities greater than the infiltration-capacity may be determined.

(a) $0^h\ 47^m$ p.m. to $1^h\ 00^m$ p.m. or $1^h\ 05^m$ p.m.
(b) $1^h\ 20^m$ p.m. or $1^h\ 30^m$ p.m. to $2^h\ 20^m$ p.m.
(c) $2^h\ 27^m$ p.m. to $3^h\ 25^m$ p.m.

(3) The various peaks in the hydrograph are then allocated to that block of rainfall which produced them.

The peak at $1^h\ 20^m$ p.m. to the rainfall between $0^h\ 47^m$ p.m. and $1^h\ 05^m$ p.m.
The peak at $2^h\ 20^m$ p.m. to the rainfall between $1^h\ 20^m$ p.m. and $2^h\ 20^m$ p.m.
The peak at $3^h\ 00^m$ p.m. to the rainfall between $2^h\ 27^m$ p.m. and $2^h\ 58^m$ p.m.
The peak at $3^h\ 28^m$ p.m. to the rainfall between $3^h\ 00^m$ p.m. and $3^h\ 25^m$ p.m.

(4) The separate periods of opportunity during which infiltration took place at capacity-rates are then established. As has been stated, this time-period will begin simultaneously with rainfall-excess, and extend to some time after the end of rainfall-excess. The difficulties encountered in evaluating the time of opportunity have been discussed elsewhere [2].

(a) $0^h\ 47^m$ p.m. to $1^h\ 05^m$ p.m. (b) $1^h\ 20^m$ p.m. to $2^h\ 30^m$ p.m.
(c) $2^h\ 27^m$ p.m. to $3^h\ 30^m$ p.m.

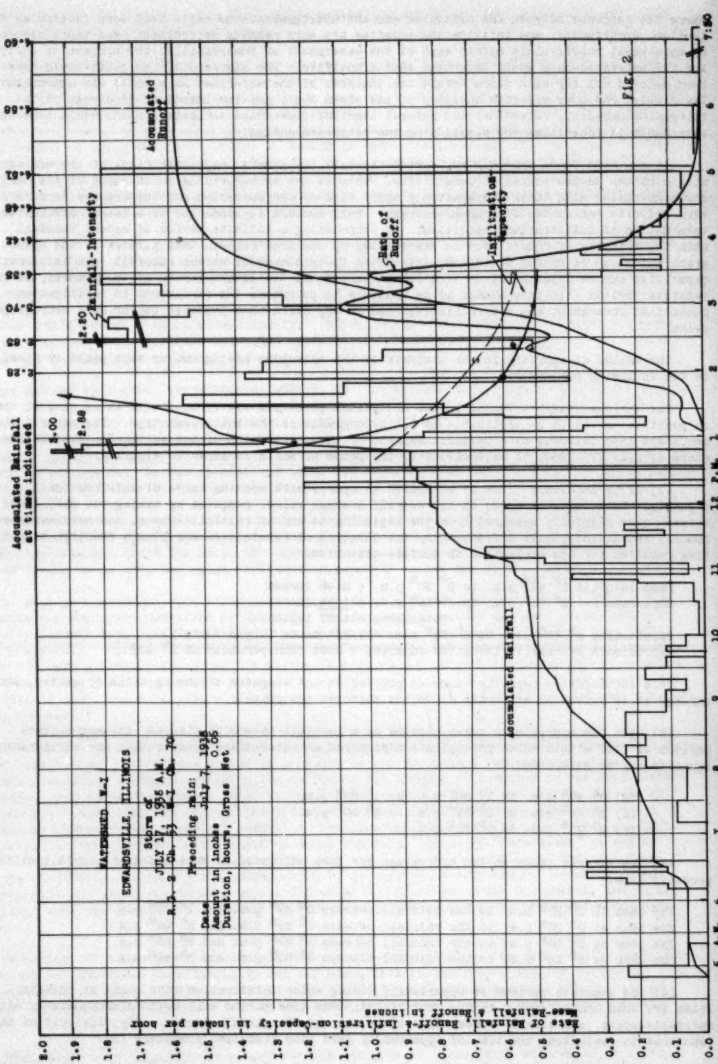

Rate of Rainfall & Runoff in Inches per hour
Accumulated Rainfall at time indicated
2.00
2.88
2.80
Rainfall-Intensity
Accumulated Runoff
Rate of Runoff
Infiltration Capacity
Accumulated Rainfall
WATERSHED W-1
EDWARDSVILLE, ILLINOIS
Storm of
JULY 17, 1936 A.M.
R.G. & Co. 53 W-1 Ch. 70
Preceding Rain:
Date July 7, 1936
Amount in Inches 0.05
Duration, hours, Gross Net
5 A.M. 6 7 8 9 10 11 12 P.M. 1 2 3 4 5 6 7:30

Fig. 2

(5) From the mass-rainfall curve, the total rainfall which occurred from the beginning to the end of opportunity is determined. This value may include precipitation which fell at intensities less than the infiltration-capacity immediately after the end of rainfall-excess. For where such precipitation occurs, it falls directly on the layer of surface-detention, thereby sustaining the surface-detention over a longer period, and thus contributing to surface-runoff and extending the period of opportunity. This effect will be negligible where the precipitation after rainfall-excess is at very low intensities. However, in the cases where the intensity of precipitation falls just below infiltration-capacity, very careful analysis is necessary to determine the time of additional opportunity and the amount of this additional rainfall which should be included in the computations.

Rainfall: (a) $0^h\ 47^m$ p.m. to $1^h\ 05^m$ p.m. = 0.57 inch
(b) $1^h\ 20^m$ p.m. to $2^h\ 25^m$ p.m. = 1.17 inches
(c) $2^h\ 27^m$ p.m. to $3^h\ 30^m$ p.m. = 1.61 inches

(6) Having determined the quantity of rainfall which produced any runoff, the next step is to determine the quantity of this runoff. Assuming at this point, for the purpose of illustration, that we are dealing with the first peak in the hydrograph, the quantity of runoff contributable to the first period of excess-rainfall is the accumulated runoff up to the time that the second rise begins plus the quantity of runoff which is still held in channel-storage. The latter quantity is obtained by projecting the point at which the second rise begins, horizontally to the right to the corresponding point on the final recession-curve, and taking the total runoff occurring after the time represented by the projected point, as being equal to the amount of runoff which would have occurred had the rainfall ceased after the initial period of rainfall excess.

Runoff to $1^h\ 30^m$ p.m.	= 0.023 inch
Runoff after $4^h\ 30^m$ p.m. (recession-curve)	= 0.03 inch
Total runoff contributable to the rainfall between $0^h\ 47^m$ p.m. and $1^h\ 05^m$ p.m.	= 0.053 inch

(7) Having determined the quantity of rainfall in any one period of excess rainfall, the quantity of runoff contributable to that rainfall and the period of opportunity, the average infiltration-capacity during the period of opportunity may be determined by taking the difference between this rainfall and runoff, subtracting the value established for retention, and dividing by the period of opportunity.

The average infiltration-capacity for the initial period of opportunity between $0^h\ 47^m$ p.m. and $1^h\ 05^m$ p.m. is then

$$[0.57 - 0.053 - 0.15 \text{ (assumed retention)}]/0.30 = 1.23 \text{ inches per hour at } 0^h\ 56^m \text{ p.m.}$$

(8) Plotting this point on the graph will quite possibly lead to some modification of the first approximation of the curve of varying infiltration-capacities. The change may be of sufficient magnitude to necessitate complete recalculation of the value first obtained.

In the example, this procedure reveals that the initial portion of the approximate curve is too low. Using the initial point computed under (7) and the overall average value, a new curve is drawn. In this particular illustration, no change in the periods of excess rainfall results.

(9) The procedure followed in calculating the average infiltration-capacity during the second period of opportunity is much the same as that for the first. The quantity of rainfall and period of opportunity are determined in much the same way with modifications necessitated by the peculiarities of the particular storm. The quantity of runoff is determined by taking the total runoff up to the time of beginning of the third rise, projecting this point across to the recession-curve in the same manner, adding the quantity of runoff represented by the area under this established portion of the recession-curve, and subtracting the quantity of runoff computed as that due to the first rain. The average infiltration-capacity during the second period of opportunity is calculated in the same manner as before. It is to be noted that in the case of the second rise, it is not necessary to make any deduction for retention-requirement unless between the periods of rainfall-excess no rain has occurred or the intensities have been too low to sustain the retention-requirements over this period. Quite often it is necessary to make some arbitrary allowances for additional retention at the beginning of subsequent periods of rainfall-excess. Here again the analysis depends on judgment and experience in handling the data.

Rainfall $1^h\ 20^m$ p.m. to $2^h\ 25^m$ p.m.		1.17 inches
Runoff to $2^h\ 25^m$ p.m.	0.2968 inch	
Runoff after $3^h\ 43^m$ p.m.	0.1986 inch	
	0.4958 inch	
Due to prior rain	0.053 inch	
	0.445 inch	0.44 inch
		0.73 inch
Additional retention		0.02 inch
Infiltration-loss		0.71 inch

Opportunity, $1^h\ 20^m$ p.m. to $2^h\ 30^m$ p.m. = 1.17 hours
Infiltration-capacity = (0.71/1.17) = 0.60 at $1^h\ 55^m$ p.m.

(10) The establishment of additional points on the curve of infiltration-capacities depends upon the number of additional peaks in the hydrograph and the degree to which they can be correlated with the rainfall-intensity diagram.

Rainfall $2^h\ 27^m$ p.m. to $3^h\ 30^m$ p.m.		1.61 inches
Total runoff	1.58 inches	
Due to prior rain	0.50 inch	
	1.08 inch	1.08 inches
Infiltration-loss		0.53 inch

Opportunity, $2^h\ 27^m$ p.m. to $3^h\ 30^m$ p.m. = 63 minutes
Infiltration-capacity (0.53/1.05) = 0.50 in/hr at $2^h\ 59^m$ p.m.

(11) When the infiltration-curve has been established as accurately as possible, the next step is to compute the supply, the quantity of rainfall represented by the portion of the rainfall-diagram above the curve, and check this against runoff. With the proper allowance for retention, the two values should be equal, but often it is necessary to alter the infiltration-line to a slight extent to accomplish this.

The adoption of the recession-curve of the runoff-hydrograph as described in item (9) is subject to some limitations and cannot be justifiably used in all instances unless full cognizance is taken of the complicating factors that may possibly be present. Some of the hydrographs of runoff involve rates, principally in their later stages, far in excess of those which the related precipitation would be capable of producing. Such a condition clearly indicates the presence, during the period of recession, of seepage-flow to the channel of ephemeral ground-water. Since such quantities of water as this ground-water flow may constitute have been accounted for as infiltration in the earlier part of the storm, allowances must necessarily be made to nullify its effect.

In the cases where the runoff is clearly in excess of the rainfall which might have produced it, the situation is immediately evident and can readily be discounted in the analysis by evaluating the quantity of this flow by means of the rate of ground-water flow which is usually indicated by the latter portion of the recession-curve. In border-line cases, where the rate of flow in the latter part of the storm is actually made up of direct surface-runoff combined with seepage-flow, the situation is more difficult to recognize. Under such circumstances, the best solution is to make use of the so-called "normal" recession-curve. Such a curve can only be obtained from simpler records of short storms that occurred during periods of low soil-moisture, and other general characteristics which indicate the total absence of ground-water flow. Long storms which occurred during relatively wet periods produce seepage-flow prior to the end of the rainfall and beginning of the recession-curve. Under such circumstances, approximate deductions must be made in the analysis of the earlier phases of the storm from the indications afforded by the recession-curve.

An additional factor must be taken into consideration in applying the recession-curve. The recession-curve of any hydrograph produced by a storm of long duration is produced by a combination of channel-storage and flow derived from the surface-detention remaining at the end of rainfall-excess. As has been explained, the amount of this surface-detention that will appear as runoff depends in part upon the rate of depletion of the surface-film by infiltration. The final recession of any hydrograph is produced after infiltration-capacities have undergone some degree of reduction; and, therefore, the quantity of runoff represented by the recession-curve is somewhat greater than the quantity which would have been produced had the rain ended at some earlier time when the infiltration-capacity was materially greater. Through a series of successive approximations, it is possible to determine the difference in infiltration-loss during the period that surface-detention remains on the surface and apply this correction to the portion of runoff evaluated from the recession-curve before deducting this from rainfall in the computations.

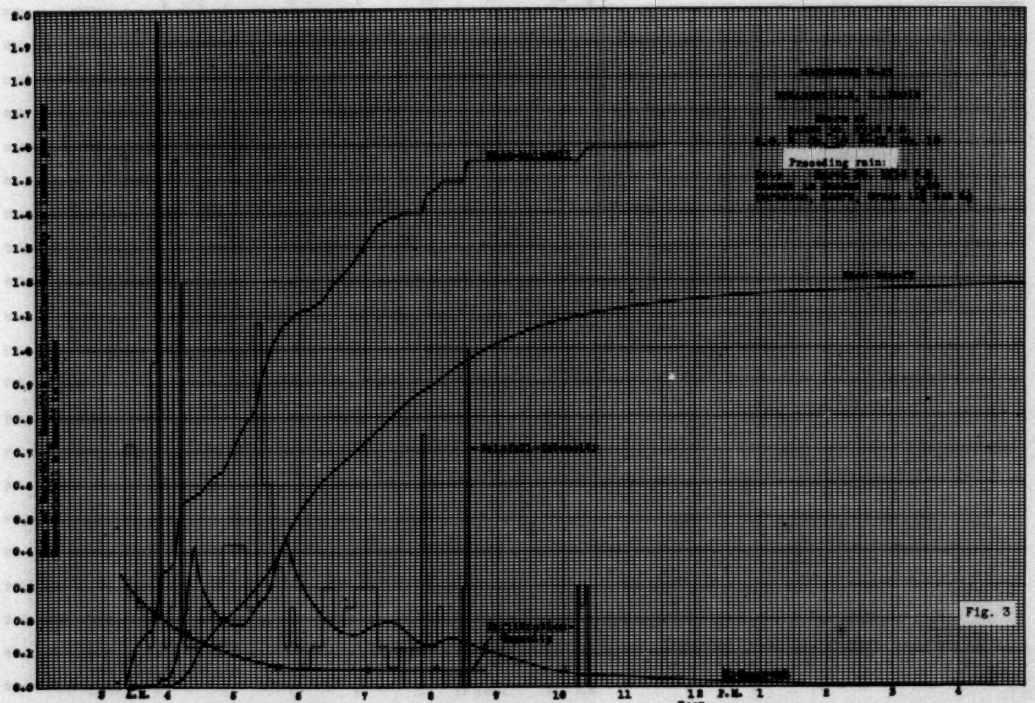


Fig. 3

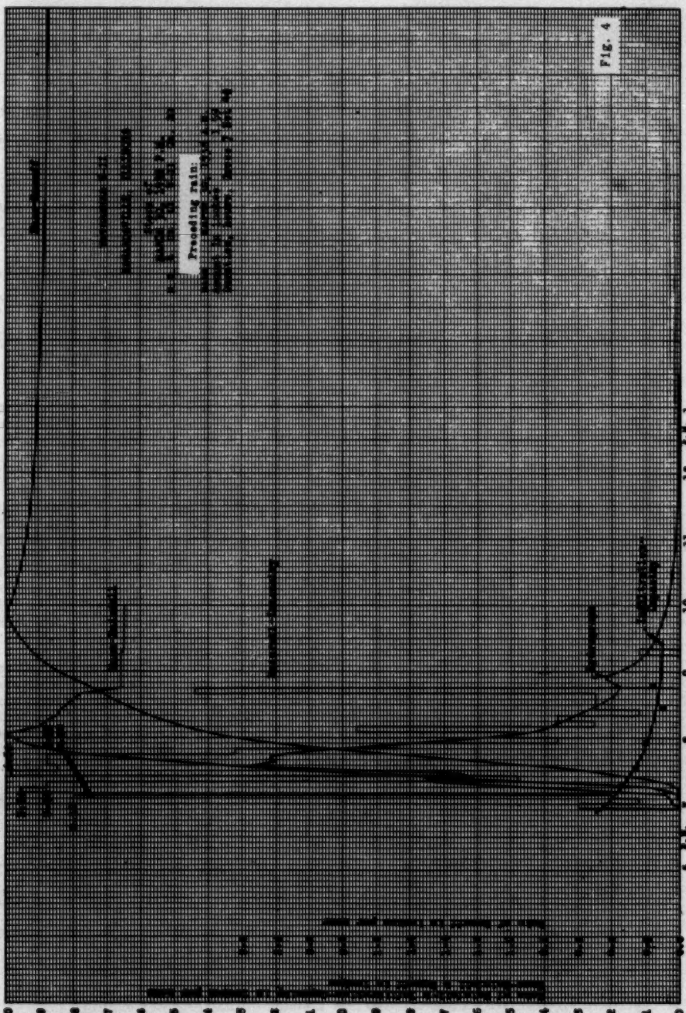

Preceding rain:
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
6
7
8
9
10
11
12
A.M.
1

Fig. 4

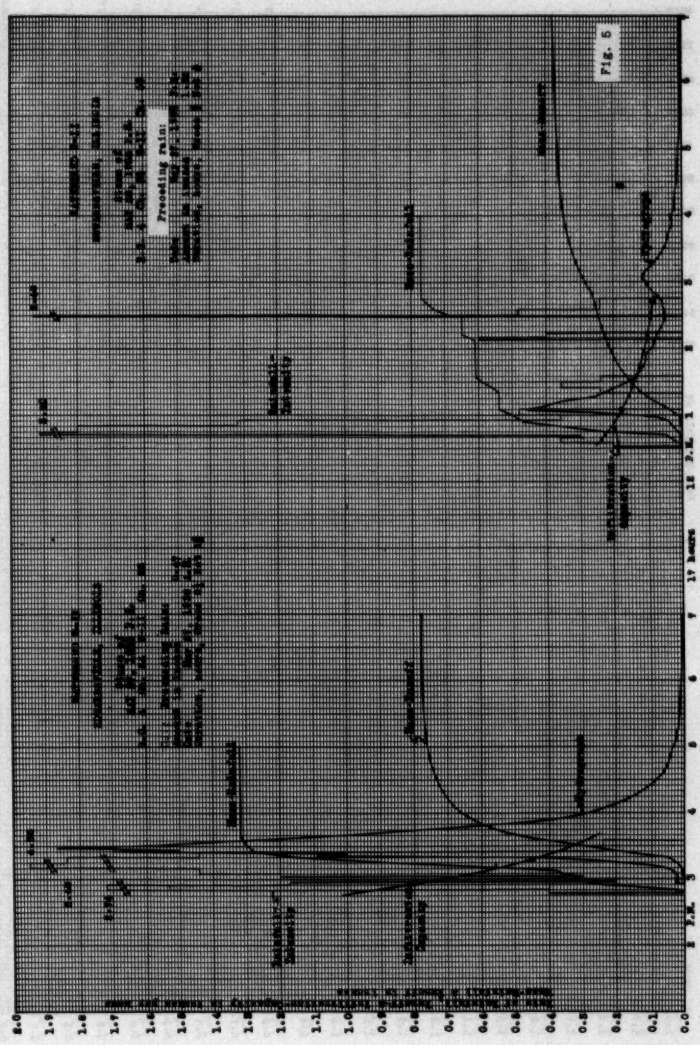


Fig. 5

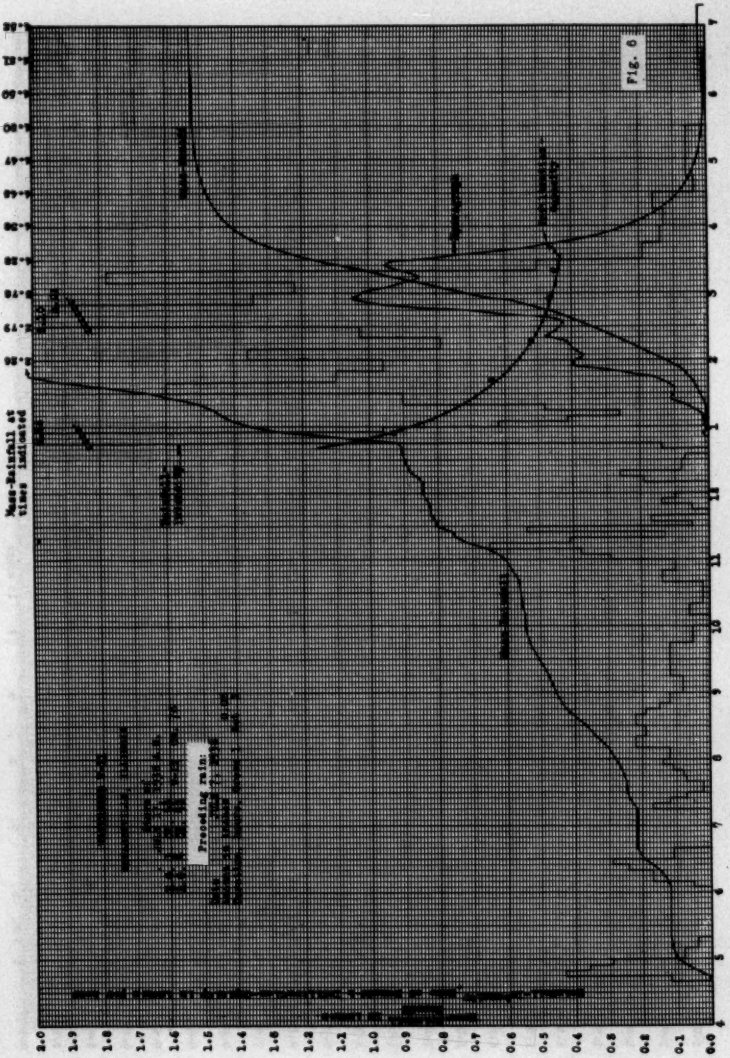
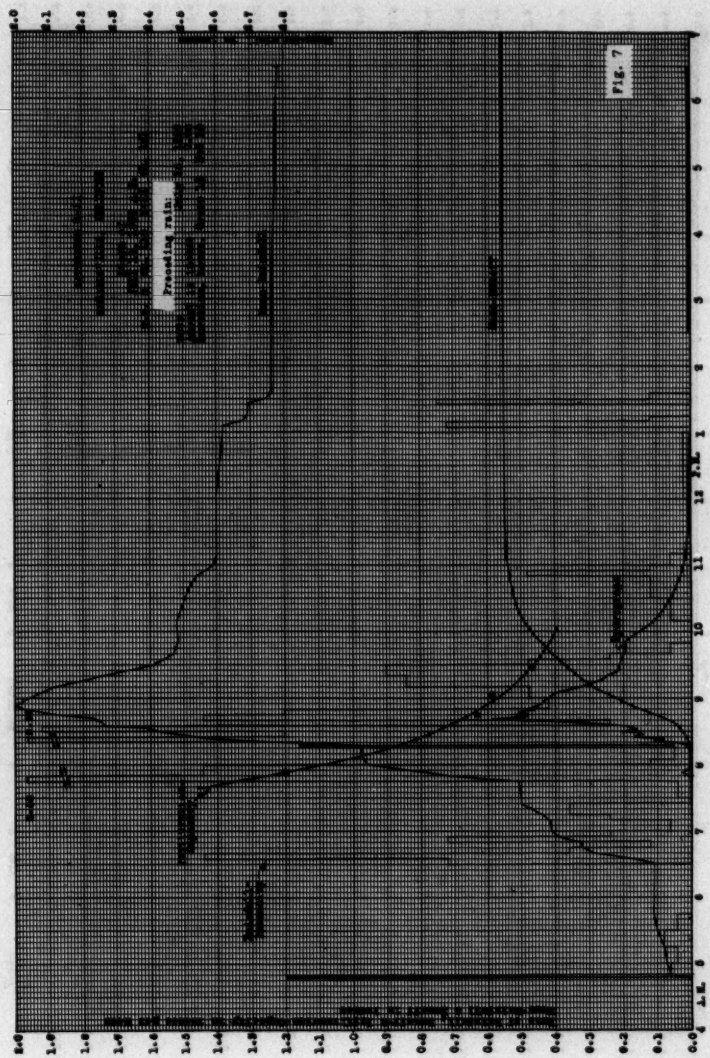


Fig. 6
Mass-Rainfall at times indicated
Preceding rain:


Preceding rain
FIG. 7

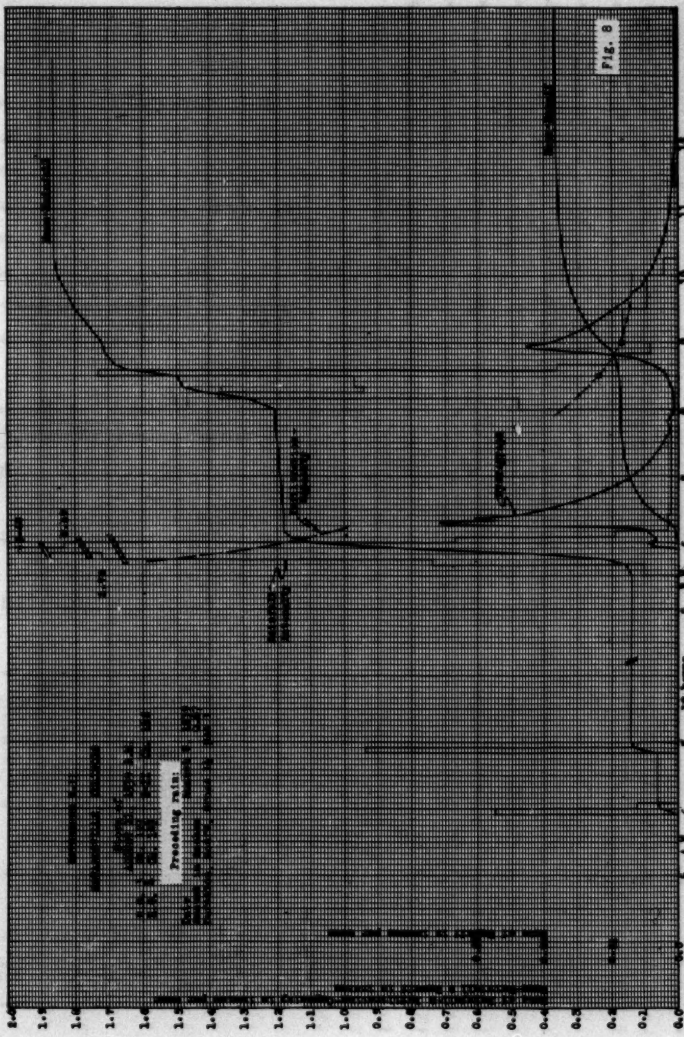
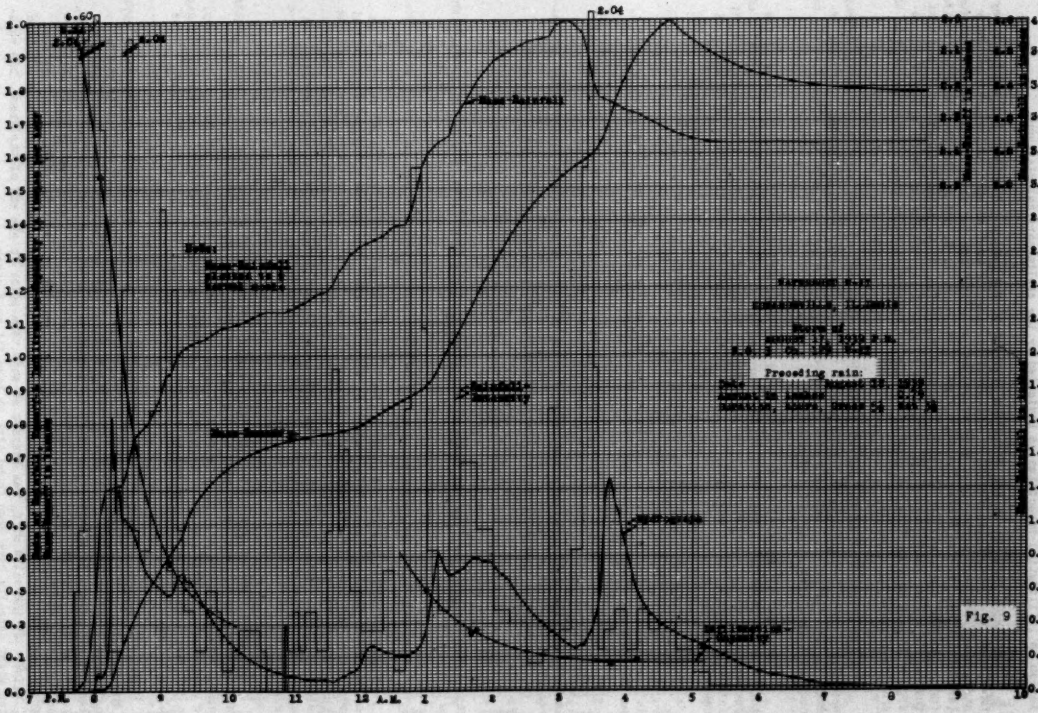


FIG. 8
Preceding rain
10 hours
5 A.M.
6
7
8
9
10
11
12
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


6.60
2.04
Preceding rain:
Fig. 9

Obviously the necessity of applying such corrections will depend upon the magnitude of the variation in infiltration-capacities as indicated by the preliminary calculations.

Summary of results--In the preceding sections of the paper, the authors believe that they have shown that the actual values of infiltration-capacity that existed during any particular storm have been determined, that such values can be determined for any storm hereafter analyzed [see actual results for other storms in Figs. 3, 4, 5, 6, 7, 8, and 9; for the complete results for all storms analyzed, see the report, previously noted, of C. Leonard Lloyd, Jr.], and that the values may be used, therefore, as a basis of hydraulic-engineering design whenever the designer is able to pick from the examples available those related to conditions comparable to the problem at hand.

In the preparation of the curves of infiltration-capacity, these were in the first instance sketched through the calculated points with a rather arbitrary visual adjustment. In some instances, the curves were extended by eye for one graph in accordance with the shape that had become available from other and longer rains.

Thereafter it appeared to be desirable to make some further analysis of the shape of the infiltration-capacity curves, and for this purpose Horton's equations as derived from Neal's experiments were utilized [3]. In this paper Horton developed his equation (5), the relation of infiltration-capacity at any time, t, to the initial value, f_0, and the final value, f_c; this curve taking the form of

$$f = f_c + (f_0 - f_c)\, e^{-K_f t}$$

He also integrated this curve and developed the expression for mass-infiltration at a time, t, in the form

$$F = f_c t + (1/K_f)(f_0 - f_c)(1 - e^{-K_f t})$$

Amalgamating these two equations and re-expressing it in terms of a short finite time, Δt, develops the expression

$$f_1 = \left[\frac{2f_c\, K\Delta t}{K\Delta t - 2} - f_2 \left(\frac{K\Delta t + 2}{K\Delta t - 2}\right)\right]$$

This is accomplished by treating mass-infiltration, F, for a short time, Δt, as being equivalent to

$$[(f_1 + f_2)/2]\, \Delta t$$

Neal's experiments were run under a condition of constant net rainfall, and therefore an uninterrupted application of infiltration at capacity-rate. The curves developed from natural rainfall on the Edwardsville watersheds necessarily had to carry over between closely adjacent storm-periods, or between parts of the storm in which the precipitation-rate dropped sensibly below infiltration-capacity. As to some such gaps, it was obvious that surface-detention was sufficient to permit infiltration to continue at capacity-rates, but in many cases this was not true.

The above equation was tested against a number of storms of practically continuous capacity infiltration, and it was found that with a value of K of 1.1, the calculated infiltration-capacity points fitted well to this form of equation. With the equation confirmed in this way, it became particularly useful in defining the infiltration-capacity curve in the vicinity of gaps in infiltration-occurrence, and was thereafter used as a basis of adjustment of the calculated points.

While it was possible to fit the calculated points to this form of curve in most cases with a single value of K, 1.1, and utilizing the indicated value of f_c for the particular storm, there were a number of instances where this application did not produce satisfactory results. Time has not permitted a sufficient study to determine the reasons for this, but as to some instances at least, it may be due to difficulty in determining the time at which f_c is actually substantially constant, particularly as to the early spring storms. It is possible that the latter part of the infiltration-capacity curve should have been assumed as being at a constant f_c-value. If the value of f_c was reached at some time prior to the end of the storm, the equation might actually have been found also to have fit such cases.

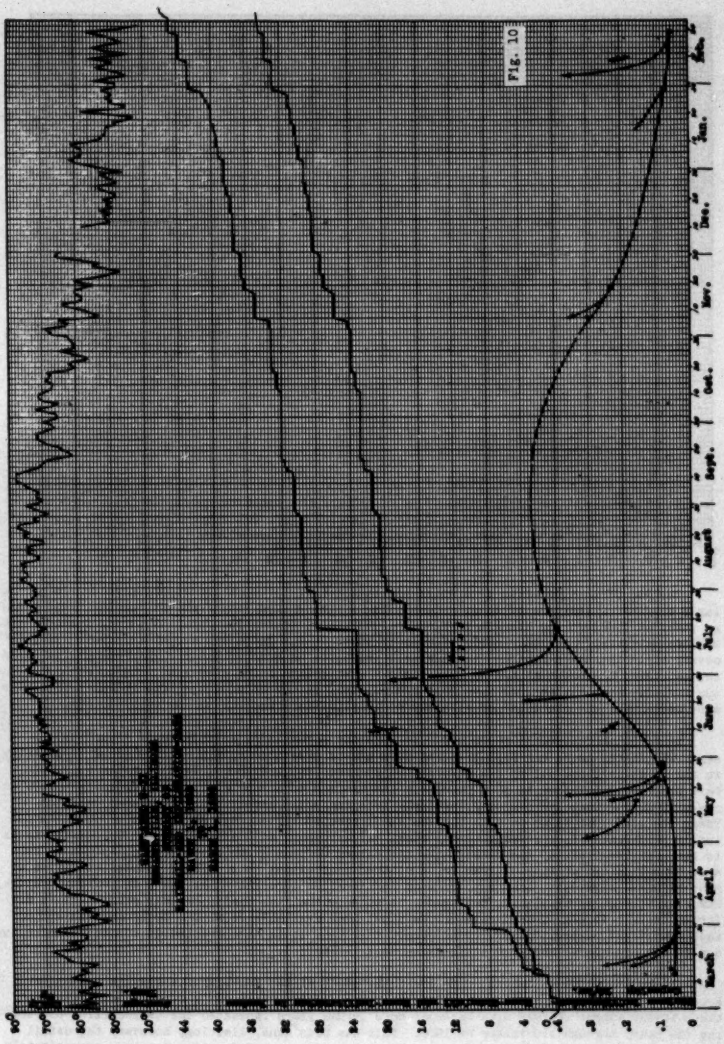
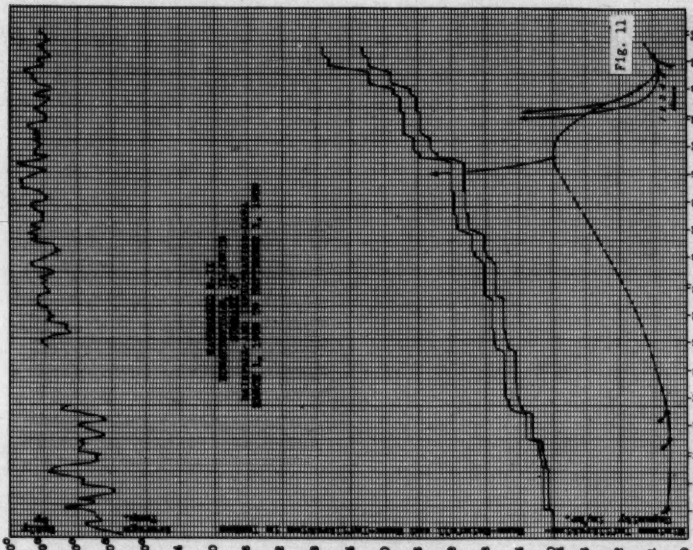


Fig. 10
March
April
May
June
July
August
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.



The use of this equation as a guide to the march of infiltration-capacity values is particularly helpful in the case of long discontinuity in the production of excess rainfall, and gives an index at least to the character of the recovery of infiltration-capacity during periods of no surface-detention. A good example of this is shown on the graph for August 17, 1939. This recovery of infiltration-capacity is also well indicated in some of the early spring storms where the gap is on the order of two or more hours. When a sufficient number of records of discontinuous surface-detention periods have been accumulated, it may be possible from these to determine more definitely the character of recovery of infiltration-capacity during such periods.

Seasonal characteristics--In order to make the accumulated material more visual in its seasonal aspect, there has been prepared here and is presented as Figure 10 a graph summarizing in the first instance all of the information secured for Watershed W-II during the year 1938. This diagram is intended to show primarily the minimum or final infiltration-capacity values arrived at during each storm-period, properly oriented with respect to its seasonal position. There has also been shown on this diagram small reduced curves showing the manner in which the infiltration-capacity arrived at these final values during each storm-period. To permit others to make further study of the reasons why the values vary as shown in these results, there has also been endorsed on this diagram certain other controlling data. These consist of curves of mass-rainfall throughout the year, of mass-infiltration throughout the year, and of temperature. Humidity-values are available, but cannot be shown within the limits of this graph. It is unfortunate that values of soil-moisture have not been available as of the beginning and end of each precipitation-period. It is understood that this is to be corrected in connection with the continuing program of research at the Edwardsville station.

It was the original intention to limit the study of the Edwardsville results to the data accumulated during one year (March, 1938, to March, 1939), but a quick comparison of the conditions in the summer of 1938 with those of more normal years indicated the desirability of carrying the study through the summer of 1939. This has been done, limiting, however, the detail study to only the more important storms. The march of mass-infiltration has been approximately determined for the whole of the added period, and is endorsed on the control-section of the graph, Figure 11.

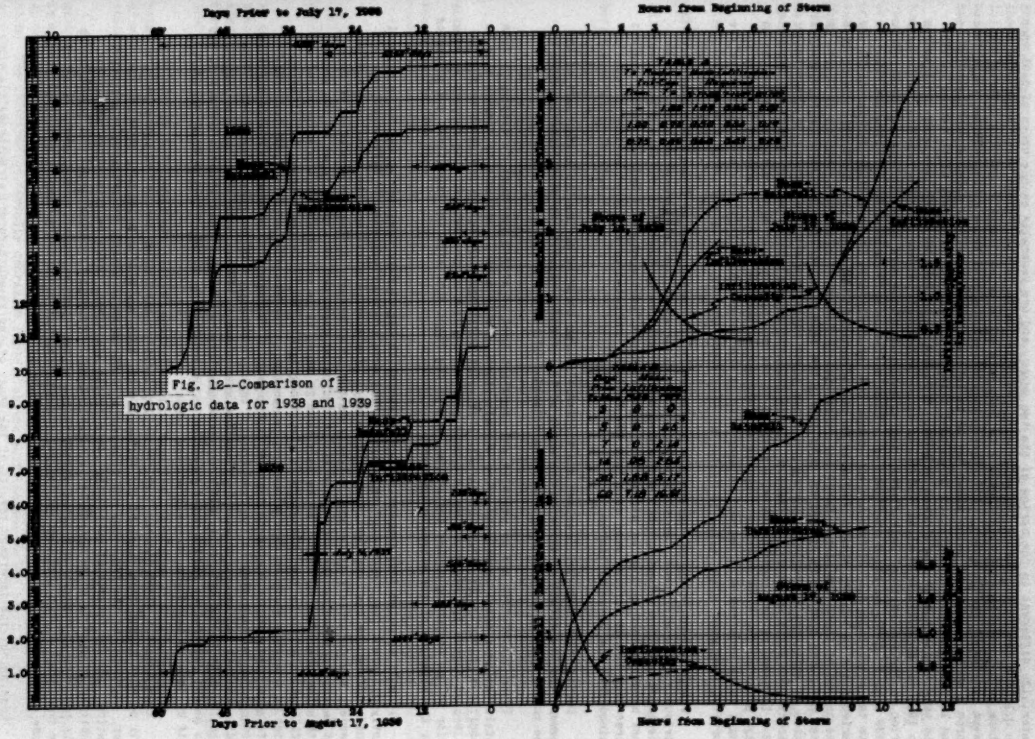


Fig. 12--Comparison of hydrologic data for 1938 and 1939

The comparison of these two years indicates that the characteristic minimum values are not materially different in the spring of the two years, and are generally on the order of 0.05 inch to 0.1 inch per hour. During the wet spring period, no high initial values were encountered, these values ranging generally from 0.2 to 0.4, seeming to depend largely upon the interval between periods of infiltration. A further comparison of the conditions during the two years from March 1 up to a critical point about May 10 is interesting. It will be noted from Figures 10 and 11 that the mass-infiltration throughout this period was approximately eight inches in 1938 and only a little over four inches in 1939. From May 10 to July 16 or 17, the mass-infiltration in 1938 was approximately eight inches and approximately six inches in 1939. During the 30 days prior to the two critical July storms, approximately one inch more mass-infiltration occurred in 1939 than in 1938, as shown on Figure 12. These differences in antecedent infiltration prior to the two comparable July storms are not great, but the difference in conditions during the 30-day period prior to the two storms does seem to be reflected in the march of infiltration-capacities. The curves of these two storms have been reproduced in the upper right-hand section of Figure 12. They are quite similar in character, have nearly the same final values, but considering identical rates of infiltration-capacity during the storm these rates appear to be related to slightly different quantities of mass-infiltration. These differences are brought out in Table A on Figure 12. It seems rather significant with respect to the one inch higher mass-infiltration in the 30 days prior to the 1939 storm as compared to 1938 that a smaller amount of mass-infiltration appears to be required with respect to each step in the reduction in infiltration-capacity for the curve of that year.

The prevalent infiltration-capacity rates during the latter part of these two summers are obviously quite different. No considerable storm occurred in the late summer of 1938, and therefore specific values are not available; but it is quite obvious that the capacity-values must have remained as high or higher than those indicated in the storm of July 17, 1938, andthat these high values carried over well into the fall, as indicated by the first available rates obtained from the November storms.

During 1939, however, frequent short intense storms occurred during the latter part of the summer, and the effect of these on the march of infiltration-capacity is significantly shown by the values which existed during the storm of August 17, 1939.

These differences are so definite and important that it seemed desirable to display in some detail the antecedent conditions prior to this storm, and to make it possible to compare them to conditions prior to the storm of July 17, 1938. The more important values are shown on the two halves of Figure 12, where on the left-hand side the conditions are set out with respect to days prior to the beginning of the two storms, and on the right-hand side the conditions are presented for the duration of the storms themselves.

It will be noted that temperature as expressed in degree-days does not appear to be significantly different for the 60-day period or for the more critical parts of it, although there are minor differences that may justify further study. The mass-rainfall and the mass-infiltration, however, are definitely different, not only in the total amounts during the preceding 60 days but particularly as to the amounts in the preceding 30 days, and very sharply as to the amount within the preceding 20 days. As to this last 20 days, it is noticeable that precipitation and infiltration prior to the 1938 storm is almost negligible, while the antecedent infiltration prior to the 1939 storm is over three inches, well distributed. The actual values for ready reference have been tabulated in Table B on Figure 12. On Table A, the amount of mass-infiltration related to each step in the reduction of infiltration-capacity has also been shown. This indicates that the amount of mass-infiltration antecedent to the occurrence of the one-inch capacity-rate is not materially different from that at the storm of the one month preceding, but the amount required to reduce capacity-rates in the succeeding steps is on the order of only half of that in the storm of the preceding month.

This analysis shows clearly that, while infiltration-capacities during the summer months will be much higher than those of the spring months, they may differ materially from year to year, depending on the frequency and sequence of occurrence of storms producing material infiltration. As the records of succeeding years become available, these relationships should undoubtedly be capable of rather definite establishment. From the records of the two years, it is only possible to suggest that final summer values of infiltration-capacity are likely to be on the order of 0.4 inch, but that during wet summers they may come down to the values comparable to those of the early wet spring period, that is, 0.05 to 0.1.

Conclusion--The important results of the study of the 18-month record at Edwardsville are those discussed in the above paragraphs and the general picture of seasonal values displayed on

Figures 10 and 11. On these two Figures there has been sketched in a diagram of minimum infiltration-capacity as it most probably existed throughout this period. It will be noticed that these values are quite similar for that part of the year from March 1 to July 16, and are materially different in the two days for the month of August. It seems important that this analysis be extended to additional records so that better confirmed probable values may be determined for the early fall months.

The short curves of infiltration-capacity during the storm-periods give a rather satisfactory picture of the mean values of the computable points that existed during the length of this record. Obviously these do not indicate the mean value during the storm, as a considerable part of the infiltration in the early section of the storm took place under higher capacity-rates which could not be computed. It seems undesirable, however, to attempt to draw any curve of initial values, as these are found to be extremely sensitive to shortly antecedent conditions. Some idea of the highest values which were found to be computable may be obtained from scanning the upper portions of the short curves shown. It is important to note that the highest values on these curves are merely the first values in each storm-period that could be calculated, and undoubtedly the true initial values are very much higher.

References

[1] Effect of soil type, slope, and surface conditions on intake of water, Nebr. Agric. Exp. Sta. Res. Bull. 112, May 1939.
[2] C. Leonard Lloyd, Jr., Report to the Soil Conservation Service on the Edwardsville, Illinois, analysis, May 1940.
[3] R. E. Horton, Analysis of runoff-plat experiments with varying infiltration-capacity, Trans. Amer. Geophys. Union, 1939, pp. 693-711.

Soil Conservation Service,
Washington, D. C.

THE INFILTRATION-THEORY OF SURFACE-RUNOFF

R. E. Horton

The manuscript for this paper could not be completed in time for publication in the "Transactions of 1940."

Voorheesville, New York

DERIVATION OF INFILTRATION-CAPACITY (f) FROM AVERAGE LOSS-RATES (fav)

LeRoy K. Sherman

Part 1

During the past two years, the writer has supervised a research and study of infiltration by the Illinois State Planning Commission. Among the results was a procedure whereby infiltration-capacities can be computed from observed average loss-rates "fav". The average loss-rates, sometimes called "average areal infiltration-capacities," are fully described by Dr. Robert E. Horton in the Transactions of the American Geophysical Union. Their derivation is now a standard practice in hydrology. Based on our work, we make the following comments.

When average loss-rates are plotted against time of duration, they show little or no correlation excepting the few, relatively small, loss-rates which are derived from long durations or with initially wet soils. The average loss-rate bears little resemblance to either initial infiltration-capacity, f_o, or ultimate infiltration-capacity, f_c.

Platting of our loss-rates by seasons, or months, showed little improvement. This statement is not a disparagement of loss-rates. They furnish one of the most useful, practical tools in applied hydrology. Numerous experiments with sprinklers on small plots show a typical curve of the progression of infiltration-capacity. It starts with a relatively high rate of infiltration. The infiltration-capacity decreases rapidly as the soil becomes wetter until, after three or less hours of effective rainfall, an ultimate, constant, or minimum infiltration-capacity is reached. Further rainfall does not reduce this ultimate infiltration-capacity.

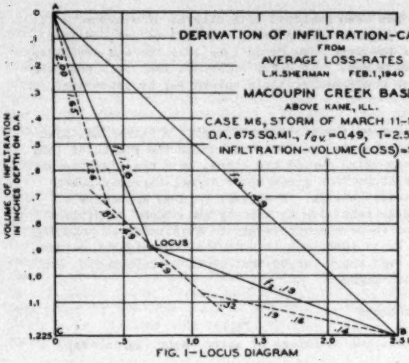


FIG. 1—LOCUS DIAGRAM

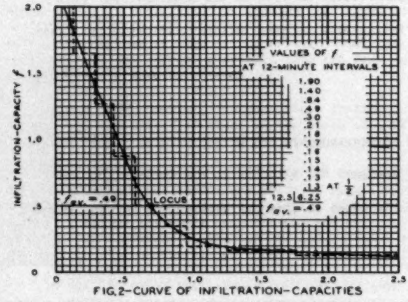


FIG.2—CURVE OF INFILTRATION-CAPACITIES

Studies of infiltration-rates of several river basins in Illinois show that, for any large basin, this progression-curve can be derived from observed loss-rates.

Definitions and symbols:

Average loss-rate, f_{av}--The figure, expressed in inches per hour, which is derived by equating the volume of rain-excess with the volume of observed run-off from a given storm.

Infiltration-capacity, f--The maximum rate at which the soil, when in a given condition, can absorb falling rain.

Equivalent infiltration-duration, T--The number of hours, from the beginning of rain to the time when rainfall ceases, during which infiltration takes place at or equivalent to f_{av}.

Example--Suppose f_{av} = 0.32 and that there were two hours of rain at 0.16 inch per hour, and also three hours of rain at 0.32 inch or more per hour. The equivalent infiltration-duration will be four hours. The volume of infiltration (a loss) will be (f_{av} × 4) or 1.28 inches, expressed in depth over the basin.

Vol = Volume of infiltration expressed in depth on the basin.

f_o = Initial infiltration-capacity, infiltration-capacity at beginning of storm.

f_1 = Average rate of infiltration for time-period above the locus.

f_2 = Average rate of infiltration for time-period below the locus.

f_c = Ultimate or minimum infiltration-capacity.

Locus--The point of intersection of the progression-curve of infiltration with the line of average loss-rate f_{av}. The locus-time is designated t_1.

The following example (observation M6) illustrates the procedure used in deriving infiltration-capacities from average loss-rates.

Time-position of locus--The first step is to find the time-position of the locus, that is, the point on the progression-curve of infiltration-capacity where f = f_{av}.

If the rate of infiltration were uniform from the beginning to the end of the storm, the curve of infiltration-capacity would be a straight line, and f would equal f_{av} at 50 per cent of the duration T. However, the rate of infiltration decreases as the soil becomes wetter.

Figure 2 is typical of the form of the infiltration-capacity curve. The position of the locus, or spot where the infiltration-capacity curve crosses the horizontal average loss-rate line, is not at 50 per cent. In general, the locus is at some period between 20 and 35 per cent of T.

Time-position of the locus, t_1

f_{av}	Per cent of T	f_{av}	Per cent of T	f_{av}	Per cent of T
0.8	35	0.5	27	0.2	20
0.7	32	0.4	25	0.1	20
0.6	29	0.3	23		

The appropriate percentage given above multiplied by a given T is the value of t_1, a time-position of the locus. The table is derived from a large number of infiltration-capacity curves of sprinkler experiments included in diagrams by Musgrave from Oklahoma and Texas, Horton in Transactions of American Geophysical Union [p. 696, 1939], and one derivation by Horner on the Soil Conservation Service plot at Edwardsville, Illinois. The given percentages decrease with long durations of T. The locus-time table used in this report is subject to revision upon analysis of additional data.

Vertical position of locus--The second step is to locate the locus in its vertical position (see Fig. 1). Duration, T, is marked off on the horizontal axis, using any convenient scale. T is at 2.5 hours in this case. From a point A as zero, on the vertical axis, the scale of volumes of infiltration is marked off. Volume is expressed in inches of depth over the basin. The bottom point at C is $f_{av} \times T = 1.225$ inches. On Figure 1, the slope of any diagonal line, such as AB, with reference to the horizontal, equals the rate in inches per hour. The line AB is drawn, and its slope is $f_{av} = 0.49$. By use of the locus-time table, locus-time was found to be at 0.7 hour. The position of the locus on this vertical line at 0.7 hour is such that it divides the volume 1.225 into two parts, y_1 and y_2, proportional to t_2 and t_1. The line from the locus to B is f_2. Expressed in general terms, the following relationships are true:

t_1 = time of locus; $t_2 = T - t$; f_1 = average f above locus; f_2 = average f below locus; Vol. = $f_{av} \times T$.

Now, $(f_1 \times t_1) + (f_2 \times t_2) = \text{Vol.}$ Also $(y_1/y_2) = (t_2/t_1)$. Therefore

$$y_1 = (f_{av} \times t_2) \quad (1)$$

$$y_2 = (\text{Vol.} - y_1) \quad (2)$$

$$f_1 = (y_1/t_1) \quad (3)$$

$$f_2 = (y_2/t_2) \quad (4)$$

Substituting the foregoing equations in the example, the following values are obtained:

$y_1 = 0.49 \times 1.8 = 0.882$ inch $\qquad f_1 = 0.882/0.7 = 1.26$ inch-hours

$y_2 = 1.225 - 0.882 = 0.343$ inch $\qquad f_2 = 0.343/1.8 = 0.19$ inch-hours

Infiltration-rate curve--To find the rates of infiltration, f, the procedure is as follows:

The line of infiltration-rates follows a smooth curve beginning with the highest value of f at A, or zero-time. It decreases with time and must pass through the locus; at this point f is 0.49, and the curve is tangent to a line parallel to f_{av}. The curve ends at B. The average of the rates f above the locus is $f_1 = 1.26$, and the average of the rates f below the locus is $f_2 = 0.19$. The sums of the increments of infiltration are: Summation of $f \times t = y_1 = 0.882$ inch and summation of $f \times t = y_2 = 0.342$ inch.

The next step is to find the individual values of f and their corresponding time-increment for the upper part of the curve. This is done by successive approximations. After a little experience, this operation is not difficult.

In the following tabulations No. 1 to No. 5, first insert all the known values, namely, f_1 at No. 3, f_{av} at No. 5, average of f_1 and f_{av} at No. 4, total of time-column t_1, total of the volume y_1. The two required figures are the value of f at No. 1 and f at No. 2. The sub-values of t_1, for the upper part of the progression-curve, known to be nearly a straight line, may be taken at equal time-intervals. If the t-intervals are not taken equally, they must increase from No. 1 to No. 5. Their total must equal t_1. The sum of the unit-volumes $f \times t$ must total y_1. The values of f must decrease from No. 1 to No. 5 and from No. 5 to No. 10. If all these rules are adhered to, no attempt at "fudging" will materially affect the values of f at No. 1 and No. 2.

This mathematical procedure is admittedly crude and we expect it to be greatly improved. It will be found helpful in trial work to add up the volumes No. 3, 4, and 5. This sum subtracted from y_1 will give a volume for No. 1 and No. 2.

No.		f	×	t	=	Vol.
1	f_o	= 2.00	×	0.14	=	0.280
2		1.65	×	0.14	=	0.231
3	f_1	= 1.26	×	0.14	=	0.176
4		0.87	×	0.14	=	0.122
5	f_{av}	= 0.49	×	0.14	=	0.069
				0.70		0.878
				$= t_1$		0.882 $= y_1$

The foregoing meets the requirements for the infiltration-capacity curve above the locus.

The infiltration-capacity curve below the locus is found in a similar manner.

A preliminary trial with five equal time-intervals of the 1.8 hours shows that this does not meet the requirements. An initial short time-unit, ending with long time-units, is required. The following values meet the requirements:

No.		f	×	t	=	Vol.
6	f_{av}	= 0.49	×	0.10	=	0.049
7		0.34	×	0.15	=	0.051
8	f_2	= 0.19	×	0.30	=	0.057
9		0.16	×	0.50	=	0.080
10	f_{10}	= 0.14	×	0.75	=	0.105
		0.19				0.342
						0.343 $= y_2$

Note: The only values derived in Nos. 1 to 10 are the first and last, at f_o and f_{10}. Values of f must increase progressively from Nos. 1 to 10, except when the ultimate value of f is obviously reached.

The curve of infiltration-capacity, Figure 2, is presented in the customary form, with horizontal time-scale and vertical ordinates of f. The step-diagram is first plotted for the ten intervals given in the preceding paragraphs. A smooth curve, shown in full line, is drawn through the locus and the steps. When ordinates of f are taken to the curve, at equal time-intervals, the average must equal f_{av} or 0.49 inch per hour.

The extension of the progression-curve, Figure 2, to the zero time-line, gives the value of f_o. This curve includes initial losses in addition to infiltration. The recession-curve of infiltration-capacity, in Figure 2, agrees almost exactly with the curve from Dr. Horton's formula given in Transactions of the American Geophysical Union for 1939.

Note the close resemblance of the derived progression-curve for 875 square miles, in Figure 2, to the curve derived from sprinkler-plot experiments. Figure 1 was inserted for description only.

By use of the above procedure, an infiltration-capacity curve has been derived from a given average loss-rate.

Part 2--Average infiltration-capacity curves and derivation of runoff

Progression-curves of infiltration-capacity are made from all of the average loss-rates (f_{av}) found for the basin. The procedure for each is similar to the example given in Part 1.

When a group of such infiltration-capacity curves are plotted, they appear as in Figure 3A, which shows curves for five storms, A, B, C, D, and E, with the higher values of f_{av}. The next higher values are grouped in Figure 3B, and those with the lowest values in Figure 3C [given in Illinois State Planning Commission Report].

When the soil, prior to the beginning of rainfall, is very dry, the curve starts at the top with a very high initial infiltration-capacity (f_o). Conversely, when the soil is wet, prior to the beginning of rainfall, the curve starts with a lower value of f_o. There is a definite relationship between the amount of water that has entered the soil and the corresponding infiltration-capacity.

If all conditions in the field were ideal, if the rain-intensities and distribution were precisely recorded, then the curve for soil initially wet would have exactly the same shape as the lower part of the curve for initially very dry soil. The value of f on the dry curve, opposite f_0 of the wet curve, has the same value as the wet curve, f_0. Likewise the volume of water at this point and succeeding points is the same on both curves.

On the Macoupin Basin, as well as on most basins, field-conditions are not ideal, and derived infiltration-curves will not be in exact accord. In order to approximate the ideal, it is therefore necessary to average the derived curves.

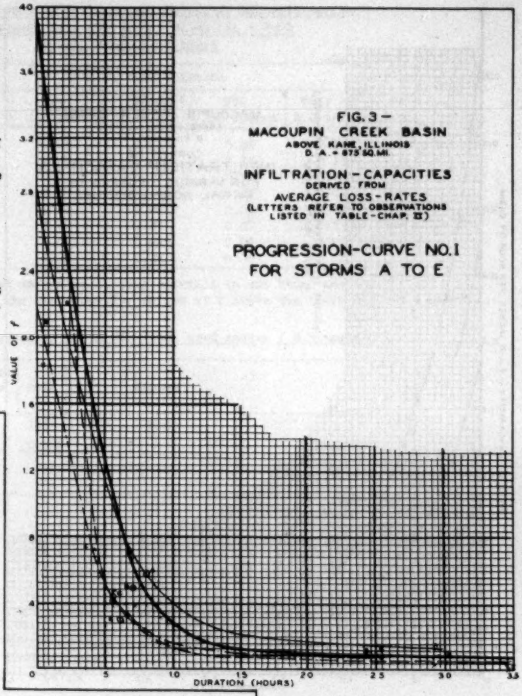


FIG. 3 — MACOUPIN CREEK BASIN
ABOVE KANE, ILLINOIS
D. A. = 875 SQ. MI.
INFILTRATION - CAPACITIES
DERIVED FROM
AVERAGE LOSS-RATES
(LETTERS REFER TO OBSERVATIONS LISTED IN TABLE - CHAP. II)
PROGRESSION-CURVE NO. 1
FOR STORMS A TO E

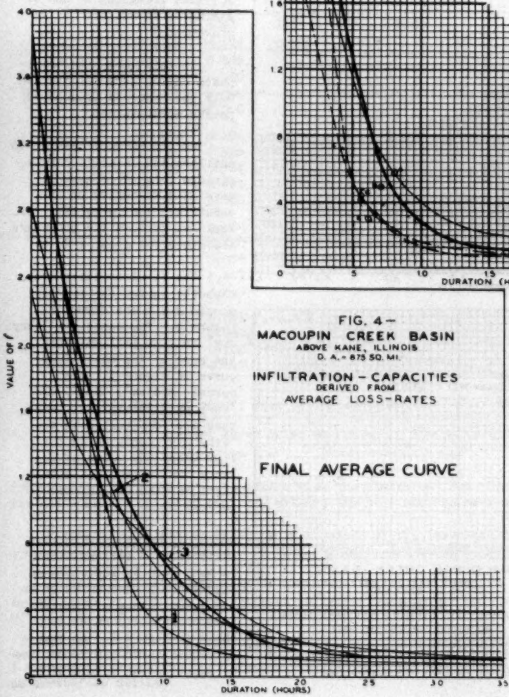
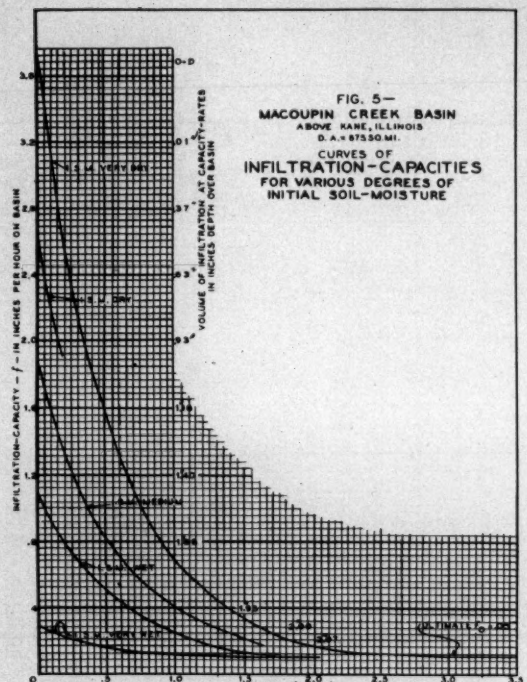
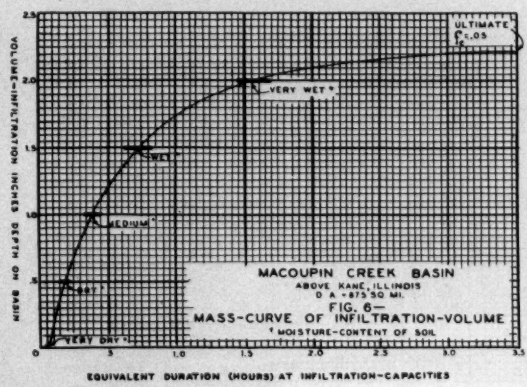


FIG. 4 — MACOUPIN CREEK BASIN
ABOVE KANE, ILLINOIS
D. A. = 875 SQ. MI.
INFILTRATION - CAPACITIES
DERIVED FROM
AVERAGE LOSS-RATES
FINAL AVERAGE CURVE

Averaging of curves--The averaging of progression-curves of infiltration on the Macoupin Basin was performed as follows: The curve having the highest observed value of f_0 is first considered. This f_0 = 3.8 for curve D on Figure 3, and is called Point 1. Then the next highest f_0 is taken. This is 2.9 for curve A. This whole curve A is moved to the right until its f_0 coincides with curve D (Point 2). Then the next highest f_0 is considered. This is 2.15 for curves B and C. On this horizontal line, the average point of curve D and A (Point 3) is noted. Curves B and C are moved to





the right to Point 3. All curves are now transferred to duration-time of the very dry curve. Any desired lower value of f, such as 1.8, is then taken and the duration-time average of all five curves (Point 4) is obtained. The same procedure is continued for other lower values of f, which are above the flat horizontal terminal lines of the curves. Finally, the duration-times, say hours 2 and 2.5, are considered. The average of the five horizontal lines of the curve-terminals are obtained at each of these times and the average points are plotted. A smooth curve through the points is the average "very dry" curve from storms A to E. It is the heavy line on Figure 3. (The foregoing method of averaging is subject to improvement.)

In this work, the transposed curves were not redrawn. Only the required transposed points were plotted.

On the Macoupin Basin, 16 infiltration-capacity curves, divided into three groups, were used to derive an accurate average curve (Fig. 4). Each set follows the procedure described for group A to E.

The final infiltration-capacity curves for the Macoupin Basin are shown in Figure 5. The curve for "very dry" initial soil-moisture is the same as the heavy-line curve in Figure 3. The curves "medium", "wet", and "very wet" initial soil-moisture are identical with the "very dry" curve below the line where the value of the "very dry" curve of f equals the f_0 of the wetter soil-curves.

Soil-moisture--The classification of soil-moisture is used here as indicated on Figure 5. A mass-curve of accumulated volume of infiltration at capacity-rates is shown in Figure 6. An equally smooth curve can be derived by substituting values of f

Table 1--Hourly infiltration-capacities, f, Macoupin Basin, drainage-area 875 square miles, f_c = 0.05 for all subsequent hours

Hour	Initial soil-moisture				
	Very dry 0 inch	Dry 0.5 inch	Medium 1.0 inch	Wet 1.5 inches	Very wet 2.0 inches
1	1.74	1.04	0.81	0.56	0.14
2	0.36	0.27	0.22	0.13	0.11
3	0.13	0.12	0.11	0.10	0.10
4	0.10	0.10	0.10	0.09	0.09
5	0.08	0.08	0.08	0.08	0.08
6	0.07	0.07	0.07	0.07	0.07
7	0.06	0.06	0.06	0.06	0.06
8	0.05	0.05	0.05	0.05	0.05

Note: Excess amount of f, over rainfall in one hour, may be applied to f of the next hour for values of f above the third hour.

Example 1--Observation C - M 28, June, used medium I.S.M. curve

Hour	Average hourly rain	Rain	f	Excess
	inch	inch	inch	inch
7 a.m.	0.126	0.126		
8	0.000			
9	0.000			
10	0.000			
11	0.000			
12 noon	0.000			
1 p.m.	0.525	0.651		
2	0.024	0.675		
3	0.464	1.139	1.14[1]	0
4	0.000			
5	0.000			
6	0.000			
7	0.000			
8	0.017	0.017		
9	0.000			
10	0.051	0.068		
11	0.246	0.314	0.10[2]	0.214
12 mid.	0.130	0.130	0.08[3]	0.050
1 a.m.	0.017	0.017	0.07[4]	

0.264 X 875 = 231 inch-miles

Observed runoff less estimated base-flow = 239 inch-miles

[1]First three duration-hours. [2]Fourth duration-hour. [3]Fifth duration-hour. [4]Sixth duration-hour.

for duration-time. This is in accord with the statement that there is a definite relation between the amount of water that has entered the soil and the corresponding infiltration-capacity.

Ultimate infiltration-capacity--All values of f_{av} (average loss-rates) derived on the Macoupin Basin which were below 0.08 inch per hour were adopted as minimum infiltration-capacities.

At the third or fourth hour of duration-time, f was found to be 0.10. For the eighth hour, f_c was taken as 0.05 for the ultimate infiltration-capacity for the Macoupin Basin (see storms Q, R, S, T, and U in table).

Applications: Estimation of runoff for large areas by infiltration-capacity curves--Table 1 expresses the various infiltration-capacities of the Macoupin Basin, referred to duration-hours as heretofore defined.

Example 2--Observation P - M 20, April, wet; used wet I.S.M. curve

Hour	Average hourly rain	Rain	f	Excess
	inch	inch	inch	inch
8 a.m.	0.034			
9	0.011			
12 noon	0.000			
1 p.m.	0.020			
2	0.116			
3	0.009			
11	0.000			
12 mid.	0.411			
1 a.m.	0.374	0.975	0.79[1]	0.185
2	0.288	0.288	0.09[2]	0.188
4	0.000			
5	0.056			
6	0.000			
7	0.018			
2 p.m.	0.000			
3	0.018	0.092	0.08[3]	0.012
4	0.000			
5	0.000			
6	0.582	0.582	0.07[4]	0.512
7	0.086	0.086	0.06[5]	0.026
8	0.300	0.300	0.05[6]	0.250
9	0.312	0.312	0.05	0.262
10	0.157	0.157	0.05	0.107
11	0.000			
12 mid.	0.000			
1 a.m.	0.238	0.238	0.05	0.188
2	0.064	0.064	0.05	0.014
				1.744 × 875 = 1526 inch-miles
Observed runoff less estimated base-flow				= 1592 inch-miles

[1]First three duration-hours. [2]Fourth duration-hour. [3]Fifth duration-hour. [4]Sixth duration-hour. [5]Seventh duration-hour. [6]Eighth duration-hour.

Table 1 was derived directly from the curves in Figure 5 by reading 1/10-hour intervals. In cases where the accuracy of the data warrants, similar tables for 30-minute or five-minute intervals may be compiled.

Derivation of runoff from hourly records of rainfall--The procedure is simple, but it is important that the reader fully understands the use of "duration-time" as defined herein. Given the sequence of average hourly rainfall over the basin:

(1) The class of initial soil-moisture is determined. Weather Bureau records are then studied for antecedent rainfalls and dry periods. The month of the year is also considered. During a single dry day in August, more soil-moisture may be lost by evaporation and transpiration than during several days in March or April. In applying infiltration-capacity curves, antecedent conditions must be studied with reference to f_o.

(2) In Example 1, it is assumed that the initial soil-moisture is "medium". During the first period, three duration-hours, infiltration-capacity is used collectively; therefore, 0.81, 0.22, and 0.11 are added, giving 1.14 inches total infiltration-capacity.

(3) Now the hours of rainfall totaling 1.14 inches are summarized. This amount of water can be taken up by the soil in the first three hours of rain. If more than 1.14 inches of rain falls in the first three hours, the excess rainfall becomes surface-runoff.

Example 3.--Observation L - M 2, November, interpolated between dry and very dry I.S.M. curve

Hour	Average hourly rain	Rain	f	Excess
	inch	inch	inch	inch
8 p.m.	0.033	0.033		
9	0.008	0.041		
12 mid.	0.000			
1 a.m.	0.053	0.094		
2	0.186	0.280		
3	0.018	0.298		
4	0.000			
5	0.087	0.385		
6	0.070	0.455		
9	0.000			
10	0.053	0.508		
11	0.000			
12 noon	0.034	0.542		
1 p.m.	0.010	0.552		
2	0.018	0.570		
3	0.309	0.879		
4	0.361	1.240		
5	0.205	1.445		
6	0.273	1.718		
7	0.336	2.054	1.820[1]	0.234
8	0.123	0.123	0.100[2]	0.023
9	0.188	0.188	0.008[3]	0.108
10	0.229	0.229	0.007	0.159
11	0.186	0.186	0.006	0.126
12 mid.	0.133	0.133	0.005	0.083
1 a.m.	0.090	0.090	0.005	0.040
2	0.029	0.029	0.005	0.000
3	0.000			
4	0.030	0.030	0.005	0.000
5	0.017	0.017	0.005	0.000
				0.773 X 875 = 676 inch-miles
Observed runoff less estimated base-flow				= 670 inch-miles

[1]First three duration-hours. [2]Fourth duration-hour.
[3]Fifth duration-hour.

(4) The initial period of rainfall necessary to produce 1.14 inches of infiltration may be very much longer than three hours. There will be no surface-runoff, however, until that infiltration-demand is satisfied.

(5) The fourth duration-hour has an infiltration-capacity of 0.10 inch. If more than 0.10 inch of rain falls in this one hour, the excess will become runoff. If the rain is at lesser rates than 0.10 inch per hour, then the recorded rainfall is summarized until 0.10 inch of infiltration has been furnished.

(6) The next duration-hour has an infiltration-capacity of 0.08 inch. Any rain in this one hour greater than 0.08 inch becomes runoff. Rain at less than 0.08 inch per hour follows the same rule as to supply of infiltration. When the eighth duration-hour is reached, infiltration-capacity becomes a constant f_c = 0.05 inch per hour. When infiltration-capacity becomes less than 0.10 inch per hour, no rain-excess can be carried over to supply infiltration during a subsequent hour.

Comments--This report presents a practical procedure for determining the volumes of infiltration and surface-runoff for large areas. It is in accord with modern concepts, researches, and experiments in scientific hydrology.

Improvements can and doubtless will be made. There is need for better figures governing the position of the "locus" than were available in Illinois. Even so, the use of an infiltration capacity table for the Macoupin Basin furnishes, with little work, runoff-figures which are much more reliable than those heretofore derived from assumed coefficients.

The derived volume of runoff is easily applied to the unit-hydrograph or the rational method for determining the distribution or peak-rates of runoff.

Description of soils and topography of the Macoupin Creek Basin above Kane, Illinois, together with procedure in deriving values of f_{av} from 21 storms, is given in a report of the Illinois State Planning Commission.

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SPRINKLED-PLAT RUNOFF- AND INFILTRATION-EXPERIMENTS ON ARIZONA DESERT-SOILS

Edward L. Beutner, Ralph R. Gaebe, and Robert E. Horton

Introduction--The original objectives of sprinkled-plat experiments conducted by the Soil Conservation Experiment Station at Tucson, Arizona, were to determine infiltration-capacities of a number of important soil-types found on range-lands on the watersheds of southern Arizona and to evaluate surface-soil conditions and various types of native plant-covers and their management in terms of their influence on erosion and infiltration. From the beginning of the work it was noted that hydrographs secured lent themselves very well to analysis and showed a good agreement with the analytical treatment of surface-runoff as reported by Dr. R. E. Horton [see 1 of "References" at end of paper].

The experiments reported herein are based on 77 separate applications of controlled amounts and intensities of artificial rain on plats 6 feet by 24 feet in size. Most of these experiments were conducted on sparsely-vegetated or bare soils and the discussion and interpretations will be largely limited to hydrologic relationships and related factors which bear directly on hydrologic phenomena.

Equipment and methods--A sprinkler-system, similar in most respects to the D-1 apparatus designed by the Soil Conservation Service in cooperation with the National Bureau of Standards, Washington, was used in these experiments. The apparatus consists essentially of four stationary 1.5 "Nulsifyre" nozzles mounted on an overhead frame, by which water may be applied at constant rates to a plat 6 feet wide and 24 feet long and to an 18-inch strip adjacent to the sides and upper end of the plat. With two nozzles in operation, water is applied at a rate slightly in excess of three inches per hour and with four nozzles discharging at a rate of approximately six inches per hour. Since slight variations in rate of application, due possibly to changes of temperature, pressure, elevation, or mechanical operation, were noted in calibrating the apparatus, check-runs were made on each site to determine the exact rate of application. This was accomplished by covering a plat with a waterproofed canvas, applying rainfall, and measuring the rate and volume of runoff which is complete and thus equals rainfall. Satisfactory distribution of water is obtained with drop-sizes comparable to actual rainfall. Runoff is measured volumetrically and timed by increments so that rate of runoff may be calculated. For the early experiments the total time of application was largely controlled by the available water-supply and was often limited to one-half hour. In most cases the rate of runoff became constant before the end of a half-hour. The entire sprinkling apparatus and study-plat are enclosed with canvas curtains to provide a shield from winds, which tend to reduce uniformity of application.

The rate and amount of soil-erosion are determined from runoff-samples taken at various intervals throughout the runoff-period. In most of the experiments reported in this paper, soil-losses were due to sheet-erosion and in only a few cases was gully-erosion induced by application of rain. Since the soil-losses were not large in most of the experiments, it is believed that the volume of soil in the runoff did not materially affect the volumetric measurements of the latter.

Characteristics of study-sites and soils--Due to the variety of topography, soil, climate, and plant conditions found in southern Arizona, it is evident that controlled-plat experiments may not include all types of country. Physical limitations made it advisable to conduct the experiments in lower watershed-areas which are or might be included in a soil-and-water conservation-program and for which little information is at present available. Sites chosen are charac-

teristic of millions of acres lying in the semi-desert portions of the watersheds of the Gila, Rio Grande, and lower Colorado rivers. A second series of experiments is being conducted at the present time in areas of the semi-desert grass-land, where ecological relationships between plant-cover, soil-erosion, and infiltration are under study.

After a study site was located, plat-locations were established. Plats were replicated at least twice for each condition to be studied and sometimes more if preliminary studies showed marked variation. Most of the experiments were conducted on soils developed under semi-arid conditions in the vicinities of Safford and Tucson, Arizona. They belong to the reddish brown, Shantung brown, and red desert-groups. Topographically the soils occur on mesas and lower foothill slopes and in alluvial swales or broad valley-bottoms. The latter soils are usually of heavier texture than the former and when unprotected by vegetation tend to puddle and seal over rapidly under the impact of rain-drops and running water. The soils vary from nearly pure sands to clay loams, although the majority of them fall into the sandy and gravelly loam-textures as do the larger areas in the field. Table 1 outlines briefly the field-characteristics of the soils studied.

Results and analysis of experiments: Averages by sites and by runs--The averages for some of the principal factors derived from the experiments are shown in Table 2. The following notes explain the column headings and give briefly the methodology of analysis of hydrologic values. Robert E. Horton has discussed some of these values more fully in a previous publication [1].

Column (3)--Average rain-intensity i in inches per hour is obtained by dividing total rainfall by duration of rain-application in hours. Rain-intensity was maintained sensibly constant throughout each experiment.

Column (4)--Initial infiltration-capacity f_o at beginning of rain or application of water in inches per hour.

Column (5)--Final constant or surface minimum infiltration-capacity f_c in inches per hour.

Column (6)--Time in hours t_c from beginning of rain or application of water at which infiltration-capacity becomes sensibly constant.

Column (7)--The exponent M, which is constant for a given experiment, in the surface-runoff-intensity equation $q_s = K_s \delta^M$; determined from logarithmic platting of q_s in terms of δ_a, where δ is the depth, in inches, of surface-detention along the outlet-end of the plat, and δ_a is the average depth, in inches, of surface-detention on the plat.

Column (8)--Index of turbulence I is given by the equation $I = 3(3.0 - M)/4$; for fully turbulent flow $M = 5/3$ and $I = 1.0$; for laminar flow $M = 3.0$ and $I = 0$. The value of I is an indicator of the fraction of the total volume of surface-runoff in which turbulence occurs. In most cases some of the flow, particularly thin films on slopes of tillage-marks, or part of the flow through depressions, may be laminar, the remaining flow being generally turbulent.

Column (9)--Exponential constant K_f in infiltration-capacity equation.

Column (10)--Coefficient K_a in the surface-runoff equation, expressed in terms of average surface-detention depth δ_a, including depression-storage, or $q_s = K_a \delta_a^M$. The value of K_a is determined directly from logarithmic platting of q_s in terms of δ_a for a value of $\delta_a = 1.0$.

Column (11)--Coefficient K_s of overland flow in terms of depth δ, along outlet-margin. The value of K_s can be derived from K_a [column (10)] and M [column (7)] by using the equation $K_s = [M/(M + 1)]^M K_a$. The coefficient K_s takes into account the effect of the principal variables--slope, roughness, index of turbulence, and length of overland-flow, in relation to surface-runoff, and its value is expressed in terms of these variables by the general equation $K_s = 1020\sqrt{S}/In\, l_o$ where l_o is the length of overland-flow in feet. This equation is not applicable if the flow is not more than one-third turbulent.

Column (12)--Roughness-coefficient n, given by the equation $n = 1020\sqrt{S}/I\, K_s\, l_o$, S being the absolute surface-slope. The difference between slope of the water-surface on the plat and the slope of the plat-surface is usually so slight that the latter is used in the computations.

Column (13)--Mass-erosion expressed in inches depth of soil at volume-weight removed during first 30 minutes of experiment.

Table 1--Field-description of sites and soils studied

Site No.	Soil-type	Surface-soil	Subsoil	Topography and origin	Degree of erosion	Cover
5 6 7	Mohave gravelly sandy loam	Reddish brown, gritty, friable, calcareous	Redder, finer texture, more compact; lime accumulations	Rolling to flat-topped terraces and fans; largely from granite	Slow sheet-erosion; coarse sand and fine gravel-erosion pavement	None, except for very little annual plant-litter
10	Gila fine sandy loam	Light brown to pinkish brown, calcareous, friable	Light-colored, stratified recent stream-deposits	Recent bottom-soils; mixed origin	Severe sheet-erosion "A"-horizon 2 to 4 inches	None
11	Gila fine sandy loam	Light brown to pinkish brown, calcareous, friable	Light-colored, stratified recent stream-deposits	Recent bottom-soils; mixed origin	Sandy overwash; "A"-horizon 6 to 10 inches	Very sparse; few burroweeds present were removed
12	Gila fine sandy loam	Light brown to pinkish brown, calcareous, friable	Light-colored, stratified recent stream-deposits	Recent bottom-soils; mixed origin	No recent erosion "A"-horizon 8 to 10 inches	Very sparse; few burroweeds present were removed
13	Gila silt-loam	Light brown to pinkish brown, calcareous, friable	Light-colored, stratified recent stream-deposits	Recent bottom-soils; mixed origin	No recent erosion	Some annual plants and litter
14	Cajon sand	Light grayish brown, calcareous, coarse	Similar to surface; deep stratified, sandy deposits	Alluvial fans and flood-plains; outwash from granite rocks	No recent erosion	Some filaree and litter
15	Ramona sandy clay-loam	Brown to grayish brown, gritty surface-soil	Heavier moderately compact, grading to gravelly sediments	Upper and lower fans; from granitic materials	Recent overwash; surface badly checked	None
16	Ramona sandy clay-loam	Brown to grayish brown, gritty surface-soil	Heavier moderately compact, grading to gravelly sediments	Upper and lower fans; from granitic materials	Slight erosion, fine gravelly erosion-pavement	Fair cover annual plants and litter
18	Mohave sandy clay-loam	Reddish brown, gritty, friable, calcareous	Redder, finer texture, very compact	Lower fans and terraces, derived from granite	Slight sheet-erosion	Sparse weed-cover
19	Teague stony loam	Grayish brown, calcareous; very rocky	Dark brown calcareous clay-loam, caliche hardpan	Alluvial fans and terraces, derived from basalt	Gravelly erosion-pavement	None
20	White house stony loam	Friable, granular, dull brown	Tough red-clay, cobbly	Upper fans; granite origin	Moderate sheet-erosion; stony pavement	Sparse cover of caliandra and grama grass
21	Sonoita sandy loam	Reddish brown medium to coarse	Compact heavy clay-loam	Alluvial fans; rhyolitic origin	Slight erosion	Sparse cover annual plants; some litter

Table 2--Averages by sites

Site No.	Slope, per cent	1	f_o	f_c	t_c, hour	M	I	K_f	K_a	K_s	n	Mass-erosion, inches
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
						Dry runs						
5	5.3	3.08	4.10	0.92	0.351	1.45	1.16	13.85	118	55	0.164	0.0031
6	8.9	3.09	4.06	1.42	0.468	1.42	1.18	14.10	357	164	0.171	0.0092
7	13.7	3.05	4.78	1.36	0.358	0.84	1.00	19.20	48	24	0.290	0.0060
10	2.0	3.31	10.98	0.63	0.279	1.50	1.13	38.80	520	236	0.039	0.0194
11	2.1	3.25	5.29	0.83	0.688	1.10	1.42	11.20	118	58	0.076	0.0088
12	1.4	3.26	5.22	0.75	0.700	2.12	0.66	14.70	1200	531	0.016	0.0127
13	0.8	3.20	4.30	0.60	0.700	1.70	0.97	5.30	270	101	0.032	0.0118
14	1.3	3.34	(a)	2.22	0.775	(a)	(a)	(a)	(a)	(a)	(a)	0.0019
15	1.3	3.32	8.38	0.28	0.171	1.50	1.12	43.25	40	18	0.266	0.0402
16	2.9	3.36	4.74	1.78	0.476	2.06	0.70	13.75	550	249	0.043	0.0039
18	3.3	3.14	4.22	0.97	0.784	2.09	0.68	9.35	1080	477	0.024	0.0150
19	2.3	3.00	4.27	0.87	0.540	2.05	0.71	11.60	1200	531	0.017	0.0083
20	4.9	3.14	9.52	1.52	0.264	2.44	0.47	28.07	1588	458	0.037	0.0051
21	2.6	3.11	6.78	1.15	0.275	2.02	0.73	25.85	480	257	0.045	0.0100
(1)	(2)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
						Wet runs						
5	5.3	3.10	5.91	0.42	0.160	1.96	0.78	35.65	1296	582	0.092	0.0073
6	8.9	3.12	5.65	0.71	0.188	2.06	0.70	38.05	1125	496	0.136	0.0188
7	13.7	3.05	3.69	0.65	0.200	1.56	1.24	25.20	200	81	0.156	0.0136
10	2.0	3.30	5.74	0.44	0.200	2.00	0.74	44.80	1810	804	0.045	0.0246
11	2.1	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
12	1.4	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
13	0.8	3.16	5.39	0.34	0.458	1.37	1.22	19.60	214	123	0.016	0.0158
14	1.3	3.34	(a)	1.29	0.498	(a)	(a)	(a)	(a)	(a)	(a)	0.0025
15	1.3	3.32	8.94	0.18	0.212	1.68	0.99	40.40	70	32	0.160	0.0336
16	2.9	3.35	6.75	1.05	0.388	2.35	0.48	18.35	1275	554	0.042	0.0054
18	3.3	3.33	5.49	0.69	0.233	2.07	0.70	29.20	1380	611	0.018	0.0095
19	2.3	3.12	5.57	0.62	0.280	2.65	0.26	23.30	2400	1032	0.024	0.0029
20	4.9	3.13	6.59	1.08	0.265	2.52	0.35	27.07	2085	601	0.048	0.0037
21	2.6	3.10	6.80	0.70	0.156	2.11	0.67	45.75	910	402	0.025	0.0075

(a) = Data on the rising side of the hydrographs were not complete enough to solve for values of f_o, K_f, M, etc. (b) = No data.

Since, with a few exceptions, each site represents in general a different soil-type and different cover-condition, it is believed that averages of all the experiments at a given site will show, as far as the number of experiments performed are adequate, true differences due to soil and cover.

An experiment was counted as a dry run if it was the first or initial run on a plat made under existing conditions of field-moisture which for most of the experiments were quite low, surface-soils frequently being nearly in an air-dry condition. A run was designated as a wet run if it followed a dry run usually within 24 hours. In many cases the soils were nearly at field moisture-capacity when the wet run was started.

It will be noted in Table 2 that there were marked differences in the value of the constant infiltration-capacity f_c for both the dry runs and the wet runs at the different sites. In general, there was a different slope at each site, but since infiltration-capacity is but little affected by slope, as shown later, this does not account for the difference. Part of the difference is, however, due to seasonal variations as runs at different sites were made in different months. Aside from this it appears that the differences in f_c at the different sites are chiefly representative of soil- and cover-conditions though the latter factor is of lesser importance since the cover was very sparse on most of the sites studied.

With respect to runoff-characteristics, the runoff-exponent M is generally higher at a given site for wet than for dry runs, seeming to indicate a smoother surface. Indications are that

Table 3--Average of runs

Runs	No. of runs	f_o	f_c	t_c	K_f	M	K_a	I	K_s	n	$\frac{q_e}{(1-f_c)}$	Mass-erosion, inches depth
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Dry	24	6.25	1.05	0.441	20.83	1.71	534	0.92	237	0.095	1.001	0.0116
Wet	21	6.12	0.64	0.249	31.86	2.02	1036	0.75	455	0.076	1.001	0.0133
Total	45	6.19	0.86	0.352	25.97	1.85	768	0.84	339	0.086	1.001	0.0124

values of the roughness-factor n are generally lower for wet than for dry runs on a given site except where the soil-surface is susceptible to severe checking and cracking between runs such as on sites 10 and 15. Increase of M and decrease of n both correspond to increased facility of runoff. Such differences between wet and dry runs have not herstofore been noticed and are probably due in this case to the effect of the initial wetting on the vegetal cover and on the soil-surface itself.

Since most of the sites had little or no plant-cover, the rate of erosion seems to be a function of other surface-conditions such as soil-puddling and erosion-pavement. Presence of the latter appears to be responsible for low rates of erosion on sites 5, 6, 7, 16, 19, and 20. The effect of slope on erosion is not clearly shown in these experiments since the range of slopes is small except on sites 5, 6, and 7 where the erosion-pavement prevented active soil-removal.

Averages of the principal factors for dry and wet runs and for all runs are shown in Table 3.

A slight reduction in initial infiltration-capacity f_o and a marked reduction in constant infiltration-capacity f_c from dry to wet runs are indicated. The time t_c required for infiltration-capacity to become constant was less for the wet than for the dry runs. The infiltration-capacity constant K_f showed a marked increase from dry to wet runs. The runoff-exponent M showed an increase and the index of turbulence I showed a decrease from dry to wet runs. The runoff on the whole was almost fully turbulent. The roughness-factor n shows a significant decrease from dry to wet runs. Column (11) has been included showing the ratio of runoff-intensity to the constant supply-rate $(i - f_c)$. q_e is the runoff-intensity at the end of the application of water. This should be equal to the supply-rate $(i - f_c)$ with constant infiltration-capacity. It will be noted that the experiments show the ratio of these quantities to be very close to unity in all cases, as it should be in accordance with the infiltration-theory of surface-runoff.

The average infiltration-capacity curves derived from all of the experiments and for wet and dry runs respectively are shown in Figure 1.

Characteristics of hydrographs--The hydrographs for a number of experiments are shown in Figures 2, 3, 4, and 5. These hydrographs cover a variety of examples of different sites with different slopes, soils, and duration of experiments.

All of the infiltration-curves have similar shapes, beginning with high values and declining rapidly for the first ten minutes after which they continue to decline slowly until a nearly constant rate of infiltration is reached. The runoff-curves show distinct waviness in many instances, especially after the flow becomes stable. The presence or absence of waviness does not appear to be closely related to soil-surface or cover-conditions but there is an indication though perhaps not significant of a relation to slope and erosion. The wave-crests vary in time from eight minutes on the steeper slopes to 13 minutes on the flatter slopes.

Relation of slope to infiltration--No consistent variation of the runoff-coefficient K_a (in terms of δ) with increasing slope could be established from these experiments. This was probably due to the fact that the effect of slope is partly masked by seasonal variations but in the main it is due to variations in soil-type, soil-surface, and cover-conditions concomitant with the different slopes. In dealing with natural watersheds, the ecological relationships must be carefully considered. Most individual soil-types do not occur on a wide range of slopes without change, a range of ten per cent being perhaps above the average. Vegetative types likewise vary somewhat with soil-types and topographic aspect.

The infiltration-capacities of soils occurring on low slopes (less than three per cent) in

this region seem to be much more variable and, when unprotected by a good vegetative cover, are probably lower than for soils occurring on steeper slopes. This is due to the fact that the flatter areas are subject to alluvial processes of deposition and removal and contain fine sandy,

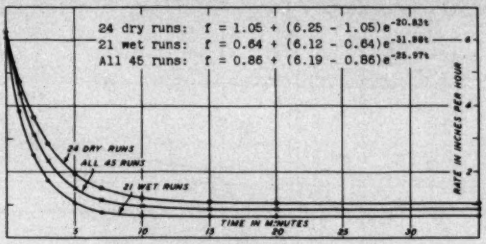
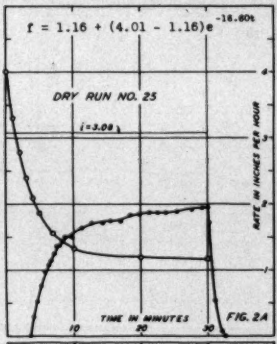
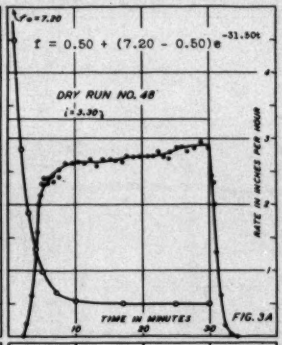
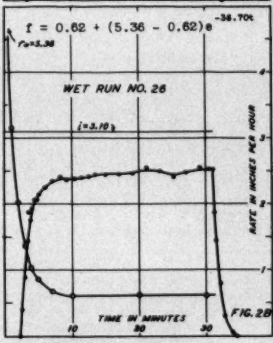

24 dry runs: f = 1.05 + (6.25 - 1.05)e^-20.83t
21 wet runs: f = 0.64 + (6.12 - 0.64)e^-31.88t
All 45 runs: f = 0.86 + (6.19 - 0.86)e^-25.97t
24 DRY RUNS
ALL 45 RUNS
21 WET RUNS
RATE IN INCHES PER HOUR
TIME IN MINUTES

Fig. 1--Average infiltration-capacity curves







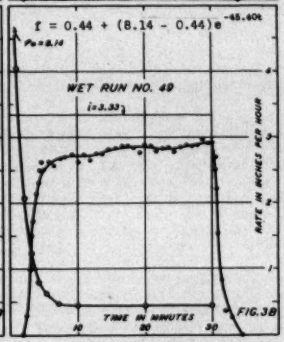


Fig. 2--Hydrographs for Site No. 6 (Tripp Canyon), Plot No. 2 (Soil, Mohave gravelly sandy loam; slope, 8.8 per cent; cover, some annual debris)

Fig. 3--Hydrographs for Site No. 10 (City Farm), Plot No. 1 (Soil, Gila fine sandy loam; slope, 2.0 per cent; cover, none)

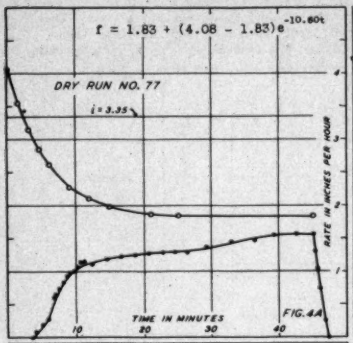


Fig. 4--Hydrographs for Site No. 16 (Beach Ranch), Plot No. 1
(Soil, Ramona sandy loam; slope, 2.9 per cent; cover, fair cover of spring annuals and considerable annual grama litter)

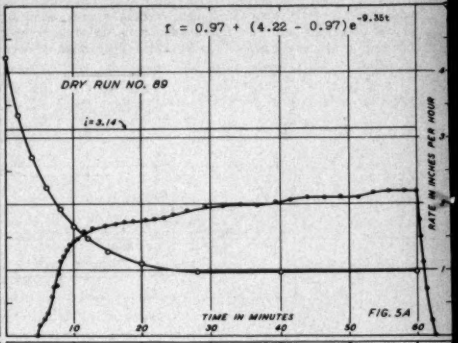
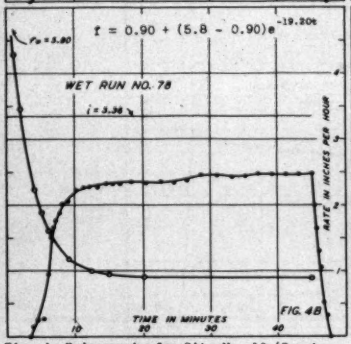
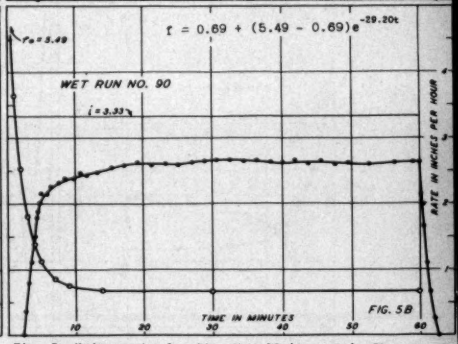


Fig. 5--Hydrographs for Site No. 18 (Artesia), Plot No. 1
(Soil, Mohave sandy clay loam; slope, 3.3 per cent; cover, 19 small burro weeds removed, 28 snake weeds not removed)





silty, and clayey soils which permit ready infiltration of water only when their surfaces are kept in a favorable condition. When a good growth of grass and plant-litter cover these soils, they may have higher infiltration-capacities than adjacent more steeply inclined and also more sparsely vegetated slopes. They may, as areas of natural water spreading, be able to absorb not only most of the rainfall but also considerable runoff from contributing slopes. When the natural balance has been upset, however, and the vegetative cover has deteriorated due to erosion or some other cause, these flat-lying soils often tend to puddle and seal over. Several of the experiments show large variations in infiltration-capacities within a slope-range of one to three per cent on the same general soil-type.

In order to eliminate variables due to soil-type and cover, experimental data for sites 5, 6, and 7 (Table 2) can be best used to note the relationship between slope and infiltration. These three sites in themselves perhaps do not furnish sufficient data to establish conclusively a slope infiltration-relation but they are typical of other experiments conducted recently and not included in this report. These sites having slopes of 5.0, 9.0, and 13.7 per cent are on the same soil-type located within 150 yards of each other on the same exposure, and have nearly the same soil-surface conditions. They are nearly identical from the standpoint of cover, being bare except for very little annual plant-debris and some leaves from surrounding creosote-bushes. No significant relationship between slope and infiltration is evident in these sites nor in other

sites not reported in this series of experiments, all tending to bear out the conclusions of other experimenters such as Duley and Hays [2] and Neal [3]. It would thus appear that other factors including cover, soil-surface and profile being equal, no significant correlation exists between slope and infiltration.

The roughness-factor--The roughness-factor n given in Table 2 has the same general meaning as the roughness-factor n in the Manning formula for flow in channels. However, in the latter case the resistance is chiefly that of true boundary-rugosity, while in the case of surface-runoff the resistance due to the surface itself may be relatively small compared with the resistance due to eddies, ineffective slope, and vegetation or other surface-obstructions such as stones and gravel characterizing the erosion-pavement on many of the sites reported in these experiments.

It may be noted that values of n for the greater number of experiments are less than 0.100 and in many cases are less than 0.050 or of the same order as the values of n appurtenant to stream-channels. Where high values of n exist such as those above 0.10, a large amount of resistance is indicated due to causes other than boundary-rugosities. These facts taken together indicate (1) that the true surface- or boundary-resistance due to rugosity on these soils is of the same order as that for natural stream-channels, (2) that the highly increased resistance occurring in a number of cases is due to surface-obstructions which may be either vegetal cover, plant-debris, or stones and gravel. The latter would have the same effect as grass in increasing frictional retardation but in addition would materially reduce the effective cross-section and the result would be a large increase in the value of n, which is computed on the basis of the entire cross-section being effective.

While the particular sites on which these experiments were made had sparse covers of vegetation and in some cases had bare soils, it is apparent that even the limited amount of ephemeral plant-growth together with scattered shrubs furnish debris which may have an important bearing on infiltration and runoff. Vegetal cover and litter may operate to increase the resistance in a variety of ways: (1) By subdividing the flow and greatly increasing the wetted perimeter; (2) by forming complete or partial debris dams on the soil-surface, through which the runoff filters slowly, with greatly increased resistance and loss of effective head or slope. The conditions at some of the sites where these experiments were carried out seem to have been peculiarly adapted to the occurrence of the latter phenomenon. It was noted on many plats that, while little plant-growth and litter were prominent on the surface before the initial run, after an application of three inches of rain, debris-dams were built up in various parts of the plat from plant-material which had originally been scattered on the surface and had been partially incorporated in the surface-soil horizon.

The soil-surface itself when in a dry condition assumes a certain roughness due to trampling effect of either one or a combination of livestock, wildlife or humans, shrinkage during the drying process, as well as other factors. Roughness due to these influences as well as that of scattered plant-materials is somewhat ironed out after an application of rain. The loose plant-debris becomes segregated into rows and dams and the attached material is more or less lined up with the direction of flow down the slope, thus offering less total resistance to runoff. Indications are that the larger depressions which are most evident in observing depression-storage are somewhat filled in with soil during the first application of rain on a plat and are thus less effective during the wet run.

The roughness-factor has an important bearing in relation to runoff-retardation, since high values of the roughness-factor correspond to low values of the runoff-coefficient K_R and low runoff-intensities and increased duration of rain necessary to bring the runoff-intensity up to equality with the supply-rate $(i - f_c)$. In fact, it is through increased resistance to surface-runoff that vegetation acts in part to reduce soil-erosion and promote infiltration. This comes about partly through reduced velocity of overland-flow, partly through increased depth of surface-detention and consequent increased infiltration of water remaining on the ground when rainfall-excess ends.

Seasonal variation of infiltration-capacity--Normal climatic conditions in southern Arizona include two rainy seasons--the summer and winter. The former usually extends from July through September and the latter from December through March. The late spring and fall are very dry especially the spring which during many years is practically rainless. This means that surface-soils of the lower elevations are often nearly in an air-dry condition just preceding the summer rains. Usually the average soil-moisture is maintained at a higher level during the winter rainy season than during the summer since little water is lost as runoff during the low-intensity rains, evaporation is much lower, and plant-growth with resulting transpiration-losses is less active during the winter.

It is not believed that the series of experiments reported in this paper lend themselves well to a study of seasonal variations of infiltration-capacity since experiments were conducted on different sites and soils throughout the year. Later experiments, however, are in progress in which repeat runs are being made on the same site. To date a number of runs have been made on several sites during the summer and again during the winter, the initial soil-moisture being nearly the same, and in most cases the infiltration-capacity is definitely lower during the winter (cooler months) than during the summer (hotter months).

Part of the seasonal variation of f_c is probably due to temperature and part to biological activities within the soil which are influenced by temperature as well as by soil-moisture. Activities of insects and other soil-fauna as well as microbiological activities are largely controlled by soil-moisture conditions as well as temperature. Studies in progress at the University of Arizona indicate that microbiological activity in range-soils is much greater during the hotter than during the cooler periods of the year and also increases during periods of higher soil-moisture.

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[1] Robert E. Horton, Analysis of runoff-plat experiments with varying infiltration-capacity, Trans. Amer. Geophys. Union, 1939, pp. 693-711.
[2] F. L. Duley and O. E. Hays, The effect of the degree of slope on runoff and soil erosion, J. Agric. Res., v. 45, pp. 349-360, 1932.
[3] Jesse H. Neal, The effect of the degree of slope and rainfall characteristics on runoff and soil erosion, Missouri Agric. Exp. Sta. Res. Bull. 280, 1938.

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A GRAPHICAL METHOD OF ANALYSIS OF SPRINKLED-PLAT HYDROGRAPHS

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The data utilized in developing the following method of analyzing hydrographs of sprinkled plats was secured by an infiltration-study party of the Office of Research of the Soil Conservation Service, under the supervision of G. W. Musgrave. The work was done on the Concho River watershed, near San Angelo, in West Texas, during the summer and fall of 1939. The data used are those from Type-F rainfall simulator-plats. This infiltrometer is the latest development of the Hydraulic Laboratory of the Soil Conservation Service. Plats were six feet wide and 12 feet long.

The sprinkling apparatus consisted of two spray heads, carrying seven specially designed spray-nozzles each, mounted on either side of the plat. The spray from the nozzles was directed upward and then arched over on the plat and surrounding border-area. The drops of this unit are rather large and fall a distance of about seven feet, having considerable force of impact. Distribution is reported by the Hydraulic Laboratory as being very good. Intensities of rainfall are dependent on the number of nozzles in use, in these studies being approximately 1.65 inches per hour when seven nozzles were in use and 3.30 inches per hour with 14 nozzles operating. Covers, or caps, were available in gangs to permit covering and uncovering nozzles at will, and practically instantaneously.

Other parts of the apparatus included steel border-plates, a tent to protect the spray from wind, a collecting trough and conduit to conduct runoff into buckets, a scales, a stop-watch, sheet-steel intensity-measuring pans, a pump, and a water-tank.

In operation, an intensity-run was first made with the pans covering the plat and conducting all rainfall on the plat into the collecting system, where samples could be collected and weighed for determining intensities. The nozzles were then covered, the pans removed, the nozzles uncovered to start the rainstorm, and the time noted. The time when depression-storage, runoff from the plat, and runoff at the sample tank began were then noted. After runoff started, continuous consecutive samples were collected and weighed. The length of time of samples was varied through the run according to the rate of change in runoff. Where the rate of change was rapid, one-minute samples were obtained. When little or no change was occurring, longer time-intervals were used.

In the particular studies reported herein, rainfall-intensities were changed at intervals

during the run. Each intensity was continued sufficiently long for the rate of runoff to become sensibly constant. At the end of each run, rainfall was shut off instantly and the residual runoff-rates were determined, as were rates of runoff during the run itself. A final intensity-calibration run was then made as at the beginning of the run. Figure 1 illustrates schematically the type of run made and hydrograph secured.

In this particular series of runs, at the end of each first wet run on each plat a second rainstorm was applied. This second storm was started at the moment depression-storage from the

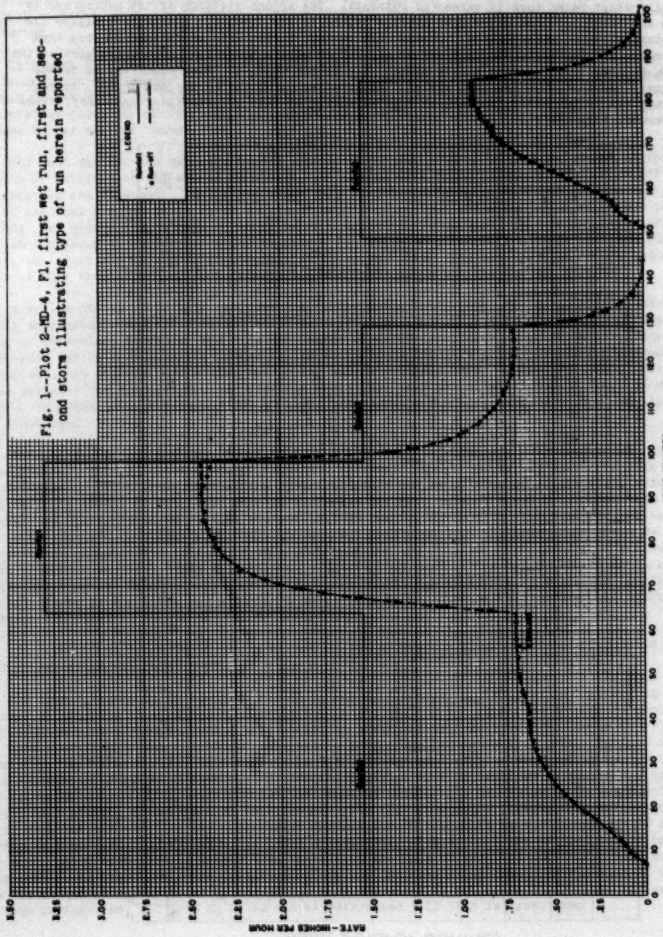
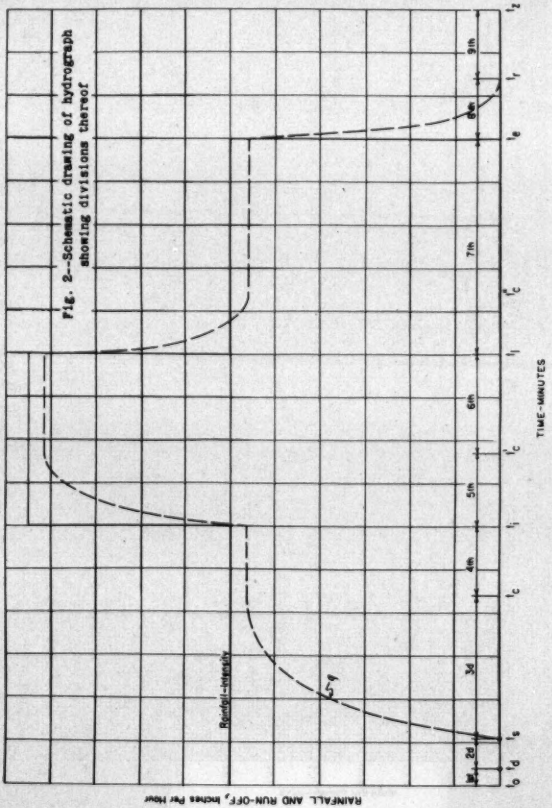


Fig. 1--Plot 2-MD-4, F1, first wet run, first and second storm illustrating type of run herein reported

first rainstorm disappeared, and was continued until the rate of runoff became sensibly constant. This second storm was applied in order to permit determination of the depression-storage capacity of each plat after the method proposed by D. D. Smith, et al, in work at Bethany, Missouri.

The hydrographs secured from the above plats were analyzed in order to determine the amount of depression-storage, the rate of infiltration, and the relationship between surface-storage (head) and rate of runoff. A preliminary examination of these hydrographs indicated the following parts, or major divisions, of each (see Fig. 2). The first is that portion from the time rainfall started, t_o, to the time, t_d, depression-storage began to accumulate. During this portion, infiltration-rates were in excess of rainfall. The second division of the hydrograph is that from the time, t_d, when depression-storage begins to the time, t_s, when runoff begins and surface-storage begins accumulating. During this period, infiltration-rates become less than rainfall-rates and depression-storage may or may not be wholly satisfied. The third part of the hydrograph is that from the time runoff starts, t_s, to the time, t_c, when runoff-rates become approximately constant. During this period, infiltration-rates may or may not change, depression-storage may be increased, surface-storage is satisfied, and infiltration- and runoff-rates are, or become, constant.



Just how, and when, the above phenomena occur cannot be measured or determined exactly. The three points on the hydrograph which can be determined are t_o, t_s, and t_c. Rainfall- and runoff-rates can also be directly measured. The rate of change, time of satisfaction and total amounts of infiltration, depression- and surface-storage cannot be directly measured.

In these particular hydrographs, there are several other distinct parts or divisions. The fourth part is that from time, t_c, to time, t_1, or t_1', when intensities were increased or lowered, as the case might be. During this portion of the hydrograph, runoff- and infiltration-rates were sensibly constant. If intensities were increased at the end of this period, the succeeding part, the fifth, of the hydrograph, is that from t_1 to t_c', the time when runoff again becomes sensibly constant, when runoff-rates, surface-storage, and possibly depression-storage is again increasing.

This part is followed by the sixth part, from t_c' to t_1, when runoff- and infiltration-rates are constant at new levels. If the intensity is then lowered, the seventh part of the hydrograph is that from time, t_1 to t_c'', during which the rate of runoff decreases to a new constant level, infiltration-rates may change, surface-detention decreases to a new level, and depression-storage may or may not change.

The next part of the hydrograph, the eighth, continues from t_c'' to another change in intensity of rainfall or the end of rainfall, t_e. During this portion, again rates of runoff and infiltration are constant. During the ninth part of the hydrograph, extending from t_e to t_r, the end of residual runoff, there is no source of supply other than the water standing on the plat, surface- and depression-storage. Runoff-rates decrease to zero during this period, and infiltration continues at an unknown changing rate. Surface-storage becomes zero at the time runoff stops, but there may be depression-storage still on the plat. The last portion of the hydrograph is that from time, t_r, to the time, t_z, when depression-storage becomes zero.

A review of the above will indicate that only during those portions of the hydrograph when runoff is constant, and after satisfaction of depression- and surface-storage, can infiltration-rates be determined directly, and with any degree of accuracy. During any period of the hydrograph when the rate of runoff is changing, three other factors, rate of infiltration and amounts of surface- and depression-storage, may or may not be changing also. There are, then, during these parts of the hydrograph, four possible variables, only one of which can be directly measured. In order to determine any one of these immeasurable factors, it is necessary to isolate the other two.

For any given plat and run, there must be some direct relationship between average surface-storage, head, D_a, in inches of depth, and rate of runoff, q, in inches per hour. If this relationship can be established, one of the above variables can be eliminated, since there must be some definite amount of hydraulic head to cause any definite rate of runoff. How can this relationship be best determined? It is evident that it must be determined from some part of the hydrograph where q is changing. It is also evident that a part of the hydrograph where depression-storage is satisfied, and where infiltration-rates are constant, or changing at a known rate, must also be used. This will eliminate use of that part of the hydrograph up to t_c because up to that time the change in average depression-storage, V_d, in inches of depth, is indeterminate as well as is the time, t_v, when V_d is wholly satisfied. During this part of the hydrograph, infiltration-rate, f, may or may not be changing.

It occurred to the authors that the part of the hydrograph after rainfall ended could be used to determine the relationship of q and D_a.

At time t_e there is on the plat all of D_a and V_d. Runoff, q_r, during the period from t_e to t_r must be supplied by D_a since V_d is contained in depressions and cannot contribute to runoff. Infiltration also continues during this period at a varying average rate over the entire plat, or, more specifically, at a constant rate over a decreasing portion of the plat. Part of the supply for infiltration, f_r, is furnished by D_a. Another part, f_v, is supplied by V_d. This latter, however, does not affect D_a. D_a, during time t_r, then is depleted by q_r and f_r, and q_r may be measured directly. There remains the problem, in order to determine D_a at any given time during this period, of determining the loss of D_a to f_r. It appears logical that the amount lost to f_r would be dependent on the opportunity offered for infiltration to occur. As runoff occurs during this period, D_a moves down the plot, successively greater portions of the plot being denied the opportunity of absorbing water, thus decreasing the rate of loss from D_a to f_r. If, due to this decreasing opportunity for infiltration, f_r has the same relationship to f_e, rate of infiltration at end of rainfall, as q_r has to q_e, rate of runoff at end of rainfall, then the amount of loss during time, t_r, from D_a to f_r can be determined. If this is true, then

$$D_a = (Q_r + F_r) = \Sigma (q_r + f_r) \qquad (1)$$

where Q_r is mass residual runoff and F_r is mass-infiltration during residual runoff, and since $(f_r/q_r) = (f_e/q_e)$

$$D_a = \Sigma q_r [1 + (f_r/q_r)] = \Sigma q_r [1 + (f_e/q_e)] \qquad (2)$$

in inches working backwards from time t_r to time t_e. If a curve of D_a-values is plotted together with a curve of q_r (see Fig. 3), then values of D_a corresponding to given values of q_r may be determined from the curves, at any given time. As stated above, these relationships are based on the assumption that f_r has the same relationship to f_e as q_r has to q_e.

This assumption was made and a series of values was thus determined for D_a and q_r for the plats in these studies. It then was necessary to determine if the above assumption was correct within practical limits. These same hydrographs offered an opportunity to make this check. On each plat, some time during each run, there was a reduction from a high rainfall-intensity to a lower intensity. Immediately following these reductions in intensity there was a period of declining rate of runoff. Immediately preceding each such time, t_1, there was a period when runoff was sensibly constant, indicating that D_a, q_c, f_c, and V_d were in stable conditions. Infiltration-rates, in all instances, changed only very slightly following changes in intensity, and in no instance more than several hundredths of an inch per hour. These parts of the hydrographs then, because infiltration changed little or none, offered excellent checks for the above assump-

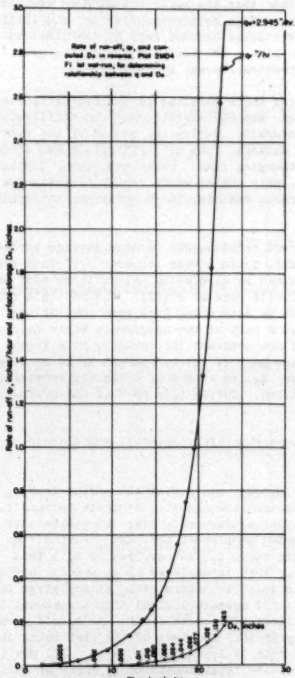

Rate of run-off, q, and computed Da vs minutes. Plot 21AD4 Fi 1d run-run, for determining relationship between q and Da
qe=2.945"/hr.
qr "/hr
Da, inches
Rate of run-off q, inches/hour and surface-storage Da, inches
Time in minutes

Fig. 3--Runoff and surface-storage curves

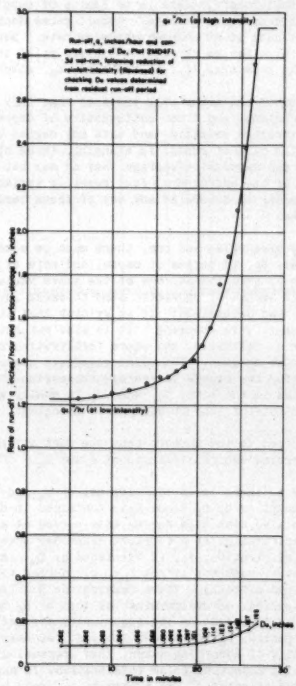

Run-off, q, inches/hour and computed values of Da, Plot 21AD4F1, 3d run-run, following reduction of rainfall-intensity (Reversed) for checking Da values determined from residual run-off period
qr "/hr (at high intensity)
qr "/hr (at low intensity)
Da, inches
Rate of run-off q, inches/hour and surface-storage Da, inches
Time in minutes

Fig. 4--Runoff and surface-storage curves

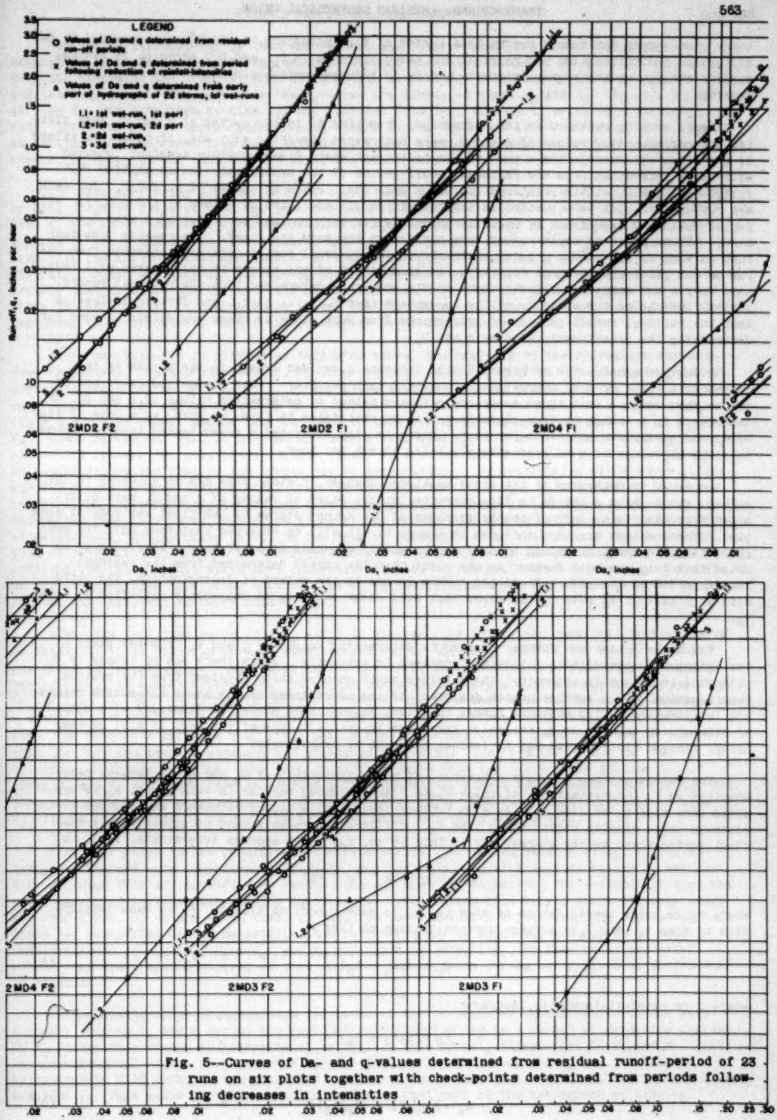

LEGEND
Values of Da and q determined from residual run-off periods
Values of Da and q determined from period following reduction of rainfall-intensities
Values of Da and q determined from early part of hydrographs of 2d storms, 1st wet-runs
1.1 = 1st wet-run, 1st part
1.2 = 1st wet-run, 2d part
2 = 2d wet-run,
3 = 3d wet-run,
Run-off, q, inches per hour
2MD2 F2
2MD2 F1
2MD4 F1
2MD4 F2
2MD3 F2
2MD3 F1
Da, inches
Da, inches
Da, inches
Da, inches
Da, inches
Da, inches

Fig. 5--Curves of Da- and q-values determined from residual runoff-period of 23 runs on six plots together with check-points determined from periods following decreases in intensities

tion. The supply for runoff during this period of the hydrograph, t_1 to t_c'', was provided by the difference in infiltration and rainfall and the difference in D_h, and D_l, where D_h is average surface-storage at the higher intensity and D_l is average surface-storage at the lower intensity.

Again working backward on the hydrograph, from time t_c'' to t_1, curves of q and D_a were plotted and corresponding values of q and D_a were determined (see Fig. 4). Now, if these new values of q and D_a, determined from a part of the hydrograph where f was sensibly constant, checked with those determined from the residual runoff-period of the hydrograph, the assumption that $f_r:f_e :: q_r:q_e$ was, within practical limits, a safe one. Pairs of values of q_r and D_a, for each wet run on each plat were plotted on logarithmic paper; and pairs of values of q and D_a for each period following reductions in rainfall-intensity for each run and each plat were also determined. These pairs of check-values were plotted on the same log paper. The results from four runs on each of six plats, a total of 23 curves (no residual runoff-data were obtained from one run on one plat) are shown in Figure 5. An examination of the curves in this Figure will indicate very close agreement between check-points and those determined from the residual runoff-period, indicating the validity of the assumption that $f_r:f_e :: q_r:q_e$, and further indicating that the residual runoff-periods of hydrographs from such plats as these may safely be used for determining the relationship between q and D_a.

A further examination of Figure 5 will indicate a decided change in the slopes of the curves at a value of q of approximately one-half inch per hour. This change indicates one of two things, namely, that there is an error in the method of determining values of q and D_a, or that there is a change in flow-characteristics or resistance to flow, or both, at a rate of flow of approximately one-half inch per hour. There is also indicated a trend toward another change in slope at values of q of approximately 1-1/4 inches per hour.

In order to determine if the above-mentioned changes in slope were due to an error in the method, rather than a change in flow-characteristics, pairs of values of q and D_a were determined from the rising part of the hydrographs of the second storms of the first wet runs of each plat. These values are also included in Figure 5. It will be observed that they have the same characteristic break at values of q of approximately one-half inch per hour. It will also be noted that they are much farther to the right than the curves determined from the residual runoff-period of the same hydrographs. This is due to the method of determination, the inclusion of a part of V_d with D_a, an error that will occur where V_d is not wholly satisfied at time t_s.

The above method was further checked by determining values of q and D_a from the parts of the hydrographs immediately following increases in intensity. Where there was no change in V_d following increases in intensity, these values again checked those obtained from the residual runoff-period. This further search for proof of the correctness of the above assumption regarding infiltration during residual runoff thus led, as indicated above, to discovery of a method of determining changes in V_d following increases in rainfall-intensities and, as will be seen later, removed difficulties met in further analysis of hydrographs.

The determination, as above described, of the relationship of D_a and q now permits determination of V_d (approximately) of these plats. As indicated earlier in this paper, V_d is supplied from time t_d to time t_c. As also further indicated, a second rainstorm was applied to the plats in these studies beginning at time t_s. Infiltration-rates should be approximately constant during these second storms, and if this is so, V_d, which becomes determinate, would be

$$V_d = (P_c - Q_c - F_c - D_a) \tag{3}$$

where P_c is total precipitation to time t_c, Q_c is mass-runoff to time t_c, F_c is mass-infiltration to time t_c, and D_a is average surface-storage at time t_c.

$$P_c = i(t_c - t_o) \tag{4}$$

where i is rainfall-intensity inch/hour.

$$F_c = f(t_c - t_o) \tag{5}$$

and

$$D_a = \Sigma q_r [1 + (f_e/q_e)] \tag{6}$$

Depression-storage, V_d, as thus determined, may then be used in further analyzing the hydrographs. This method permits the determination of the total amount of V_d up to time t_c, but does not determine the time t_v, when it is wholly satisfied. This must be estimated in analyzing the hydrograph. Two points on the V_d-curve are fixed, at times t_d and t_c. V_d will be zero at time t_d, and a maximum at time t_c, and continue from that time to t_1 or t_e as a straight line, provided that no appreciable erosion occurs during the runs. If erosion does occur, V_d may be continuously decreased from some maximum to almost zero during the run or runs. V_d can increase, as well, during runs, by the formation of trash-dams in small drainageways on the plat.

In these particular studies, a third approximate point on the curve of V_d can be determined by obtaining its value at time t_e, in the second rainstorm of the first wet runs. An inspection of the runoff-curve will further assist in estimating the shape of the V_d-curve. If the q-curve is steep and smooth, it indicates the V_d-curve is also steep, that V_d is early satisfied. If the curve is flat and smooth, it indicates V_d is slow in being satisfied or that infiltration-rates are high and decreasing slowly. If the runoff-curve has "steps" in it, it is certain that V_d is not wholly satisfied before the time these "steps" occur, because the abrupt rises in the q-curve, following these steps, flat portions, are caused by new areas of the plat beginning to contribute to runoff rather than to depression-storage.

After the V_d-curve is plotted as indicated above, the analysis of the hydrograph may proceed as follows. Mass-precipitation, P, from time t_o, should be plotted. A curve of D_a-values corresponding to rates of runoff, q, at any given time may then be plotted, using the V_d-curve as a base, that is, adding D_a-values to V_d-values. The result of this will be a curve to t_e of $(V_d + D_a)$. Mass-runoff should then be added to this curve, giving mass-loss curve of Q, D_a, and V_d. These curves may best be plotted by working from time t_e, t_1, or t_l back to time t_o. The difference between the mass-precipitation curve, P, and the mass-loss curve $(Q + D_a + V_d)$ will be mass-infiltration (neglecting losses due to evaporation). By determining differences at successive points between mass-rainfall (supply) and mass-loss $(Q + D_a + V_d)$, ordinates of a mass-infiltration curve may be obtained and that curve plotted. Rates of infiltration may then be determined from this curve, since the slope of the mass-curve, taking into account proper units of measurement, at any given point, is the rate of infiltration at that point. The determination of rates of infiltration at successive points will then permit the plotting of a curve of infiltration-rates. This curve must intersect the rate of rainfall-curve at time t_d. The rate of infiltration from this point back to time t_o is indeterminate but may be approximated by projecting the infiltration-curve back to t_o.

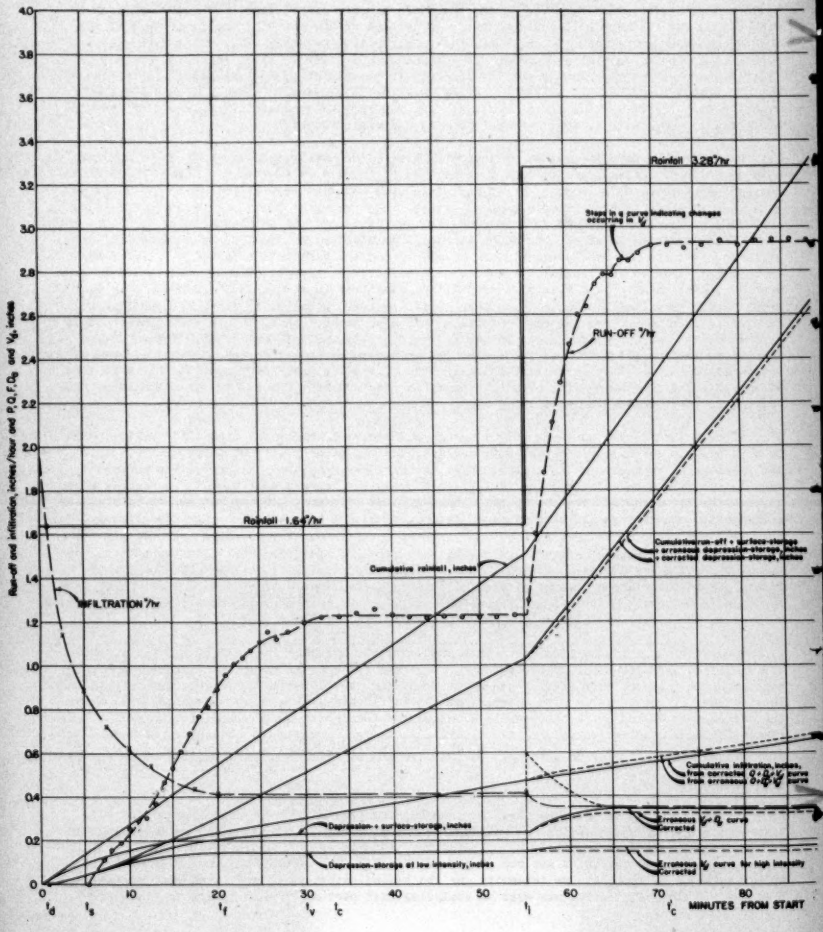
After the mass-loss curve $(Q + D_a + V_d)$ is plotted, and before the mass-infiltration curve is obtained, it is possible to make some corrections in the early part of the V_d-curve, which was drawn in by estimation. As stated above, the difference between this mass-loss curve and mass-rainfall is mass-infiltration. This last curve should have a continuously decreasing slope to the time t_f, when infiltration becomes constant, and from that time to the end of rainfall or a change in intensity should be a straight-line curve with a slope equal to f_c. Conversely, then, the mass-loss curve $(Q + D_a + V_d)$ should have a continuously increasing slope to time t_f, when infiltration becomes constant and should be a straight line from that point to time t_e, or t_1, or t_l, whichever applies. The portion of this curve from t_e, t_1, t_l back to time t_c, if total D_a and V_d are known, can be plotted quite accurately, should have a slope equal to q_c, and this portion will aid materially in correcting the V_d-curve from this point, t_c, back to time t_d. V_d will be the difference between the corrected mass-loss curve and $(Q + D_a)$.

A further check is now possible. As stated earlier, the total amounts of D_a, V_d, Q, and F can be determined with considerable accuracy, but that the rate of change of V_d and f, and the time at which they are satisfied or become constant must be estimated. The determination of the total amount of infiltration permits checking the infiltration-rate curve, since the area under the rate-curve, up to any given time, is equal to the cumulative infiltration to that point. If these two quantities differ materially, the rate-curve may be adjusted, and curves of mass-infiltration, F, $Q + D_a + V_d$, $D_a + V_d$, and V_d may again be corrected. By this trial-and-error method very close approximations of true rates of infiltration during early parts of storms may be obtained.

It was stated above that searches for proof of the accuracy of determination of the relationship between D_a and q during the residual runoff-period led to a method of detecting changes in V_d following a change in intensity of rainfall. This is well illustrated in Figure 6. This is the hydrograph of the third wet run of plat 2-MD-4-F1. The amount of V_d was determined to be approximately 0.15 inch, at low intensity, by the second rainstorm of the first wet run two days previously. This value of V_d was used in analyzing that part of the hydrograph to time t_1.

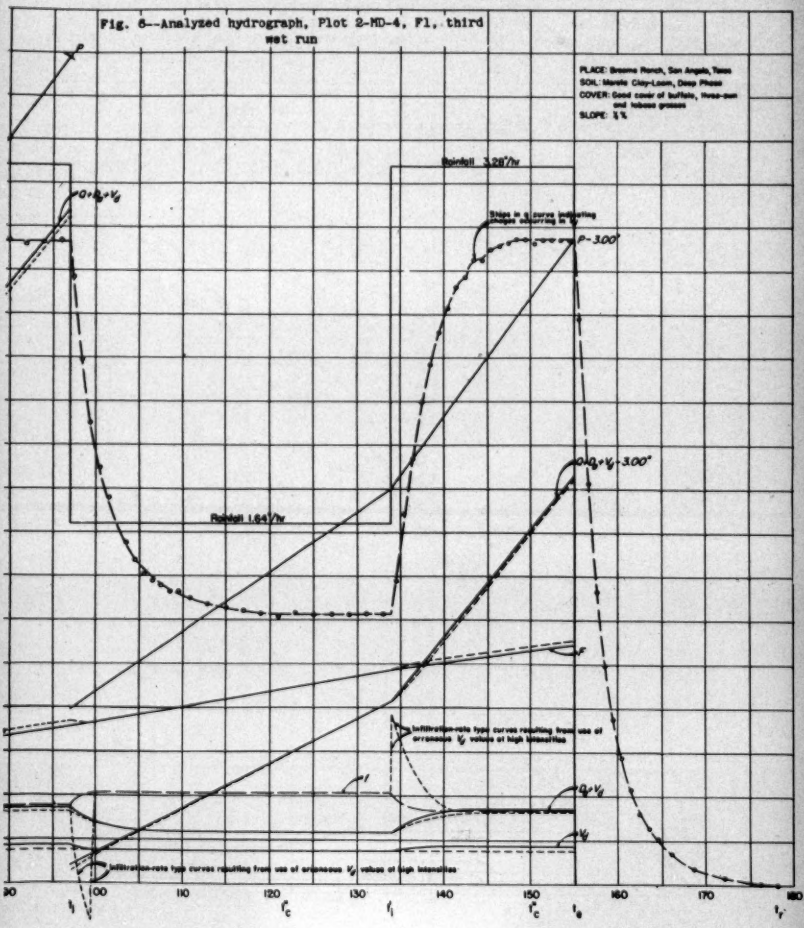
55.25 minutes. An inspection of the q-curve during this part of the storm reveals a "step" at 27.50 minutes. Also the q-curve is rather flat up to this time. This indicates that depression-storage was not wholly satisfied until time t_v, approximately 30 minutes. From this point back to time t_d, the V_d-curve gradually becomes lower. This part of the curve was estimated and D_a and Q were added to it.

The resulting mass-curve was then drawn in so that it had a continuously increasing slope up to time t_f, and as a straight line from there on to time t_l, and the V_d-curve was corrected.


Rainfall 3.28"/hr
Steps in q curve indicating changes occurring in V_d
RUN-OFF "/hr
Rainfall 1.64"/hr
Cumulative rainfall, inches
INFILTRATION "/hr
Cumulative run-off + surface-storage
Erroneous depression-storage, inches
= corrected depression-storage, inches
Cumulative infiltration, inches;
from corrected Q = P-F-V_d curve
from erroneous Q = P-F-V_d curve
Erroneous V_d = Q curve
Corrected
Depression + surface-storage, inches
Depression-storage at low intensity, inches
Erroneous V_d curve for high intensity
Corrected
Run-off and infiltration, inches/hour and P, Q, F, D_a and V_d, inches
MINUTES FROM START
t_d t_s t_f t_v t_c t_l t'_c

Points for the mass-infiltration curve were then obtained by obtaining the difference between the mass-precipitation curve and mass-loss curve. This curve has a continuously decreasing slope up to time t_f, and from there to time t_1, is a straight line with a slope equal to f_c. At time t_1, 55.25 minutes, the intensity of rainfall was increased. If V_d does not change with this increase in intensity, it would continue as a straight line indicated by the broken line in Figure 6. D_a-values, obtained from the curves of q and D_a in Figure 5, added to this V_d-value would give the broken ($D_a + V_d$)-curve. And cumulative runoff added to this curve produces the broken mass-loss curve ($Q + D_a + V_d$). The difference between the P-curve and the broken mass-

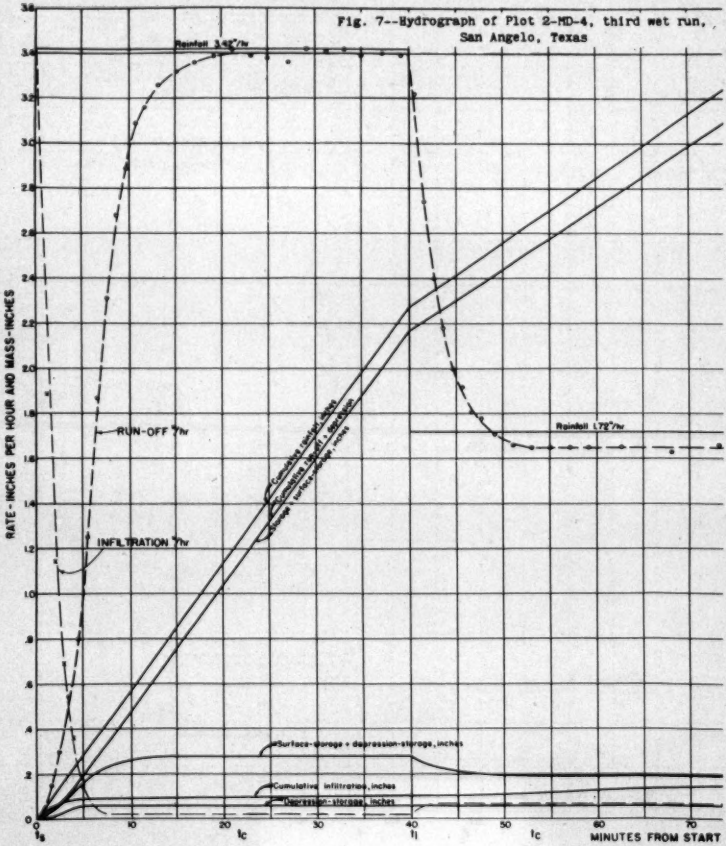
Fig. 6--Analyzed hydrograph, Plot 2-MD-4, F1, third wet run



loss curve results in the broken F-curve. It will be noted that this F-curve is convex for a few minutes subsequent to time t_1. This is hardly possible since the slope of this line is the rate of infiltration and this type of a mass-infiltration curve would indicate an infiltration-curve similar to the broken schematic f-rate curve in Figure 6.

Pairs of values of D_a and q were determined for the period t_1 to t_c', as indicated earlier, in order to check D_a-values determined by the periods t_1 to t_c'' and t_e to t_r. These values determined from t_1 to t_c' were greater by a maximum of some 0.02 inch. An inspection of the q-curve during the period t_1 to t_c' revealed two small steps at 65 and 67 minutes, indicating changes were occurring in V_d. This confirmed observations made in the field which indicated that the upper right-hand corner of the plat contributed to runoff only during high intensities, apparently having an infiltration-rate higher than the low rainfall-intensity. Curves of V_d, $(V_d + D_a)$, and $(Q + V_d + D_a)$ were corrected for this amount of change in V_d, the amount of the difference

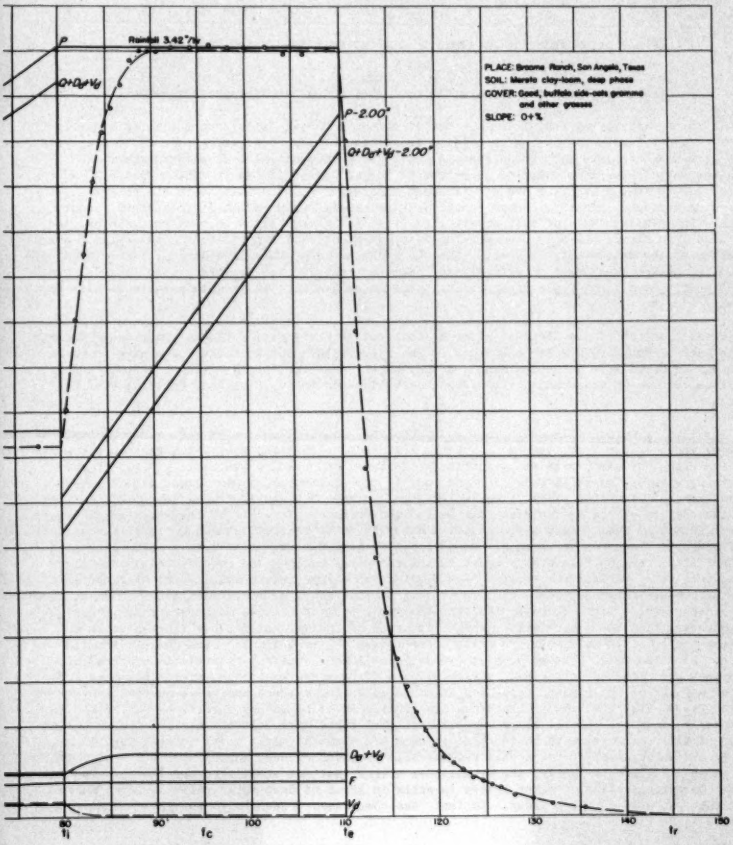
Fig. 7--Hydrograph of Plot 2-MD-4, third wet run, San Angelo, Texas



in the two sets of D_a-values, and the solid curves in Figure 6 were the result. The new F-curve has the logical shape and the proper slopes. The scale used, however, was not sufficiently large to enable determination of points on the rate of infiltration-curve immediately following changes in intensity. Such small changes in infiltration-rates are outside the limits of this method, it is felt.

A hydrograph where there is no appreciable change in V_d with changes in rainfall-intensities is illustrated by Figure 7. In this hydrograph, D_a-values determined during the period from t_1 t_c check very closely with the values of D_a determined from the residual runoff-period, thus indicating no change in V_d with changes in rainfall-intensity.

There has, as yet, been no opportunity to determine how the above method of hydrograph-analysis will apply to other soil-types with greater slopes, and different cover. It is hoped



that sufficient details of the method have been given so that others may be able to check it. It is felt that this method offers a means of rather close approximation of rates of infiltration, amounts of depression- and surface-storage, and relationships between surface-storage, head, and rates of runoff. More information under other conditions of terrain, soils, and cover are required before the degree of accuracy of the method can be determined.

Considerable information for the development of this method of hydrograph-analysis has been obtained from a paper by R. E. Horton, "Analysis of runoff-plat experiments with varying infiltration-capacity," published in the Transactions of the American Geophysical Union for 1939 [part 4, pp. 693-711], and a report of D. D. Smith, et al, of work done at the Bethany, Missouri, Soil Erosion-Control Experiment Station. Acknowledgment of this assistance is hereby gratefully made.

Soil Conservation Service,
Washington, D. C.

GROUND-WATER RECHARGE IN AREAS OF DEEP WATER-TABLE IN THE GREAT PLAINS

R. C. Cady
(Published with the approval of the Director, U. S. Geological Survey)

It is unanimously agreed, I think, that of the water which falls upon the Earth's surface, a part runs off toward the sea, a part is at least temporarily detained, a part of it evaporates, and a part sinks beneath the ground-surface. But among students of that water which sinks beneath the Earth's surface, complete agreement as to the course it then takes has not always prevailed. Ground-water hydrologists have assumed that water can and does reach the water-table by descending through a great thickness of subsoil in the semi-arid upland divides of the Great Plains. But many students of soil-moisture and its use by vegetation in the Great Plains have concluded from their soil-moisture sampling that water does not descend to the water-table where the depth to the water-table is great. Thus Cole and Mathews state in Technical Bulletin 637 of the United States Department of Agriculture, page 69, that "It can be safely said, however, that on the short-grass land of the Great Plains there is no penetration of upland surface-water to the water-table."

I shall present three lines of evidence that cumulatively seem adequate proof that recharge to the zone of saturation does take place in the upland plains of Nebraska. The data on which the study is based were collected during ground-water investigations carried on by the Federal Geological Survey in cooperation with the Conservation and Survey Division, University of Nebraska.

The first line of evidence is mainly inferential, but it illustrates the reasoning that has led many ground-water hydrologists to believe without much question that recharge occurs beneath the high upland divides, even though definite proof was not readily available. Figure 1 shows the hydrographs of two wells (Nos. 339 and 246) in the Platte Valley near Grand Island [see 1 of "References" at end of paper]. The water-level in well 339 ranged from a depth of a little over two feet to a little over five feet below land-surface. In well 246 the water-level ranged between 16 and 17 feet. We observe that the water-level in well 339 responds almost immediately and fluctuates widely as the rainfall varies, but in well 246 the water-level, which lies at a greater depth, remains relatively stable during the early part of the record, and slowly rises during the latter part of the record. Its fluctuation covers only a small vertical range, but the rise, though retarded, continues over a long period. This general relation has been observed on a wider scale. In the State-wide observation-well program carried on in Nebraska it has been observed that the water-level in wells in areas of shallow water-table fluctuates in much the same manner as in well 339. In wells where the water-level is at depths roughly from 15 to 50 feet the water-level behaves much as it doesin well 246. The water-levels in observation-wells that are situated on the high upland divides of Nebraska where the water-table lies 100 feet or more below the land-surface have shown no appreciable trend during an observation-period of five years. Their slight fluctuations are considered to be caused chiefly by variations in atmospheric pressure. As the water-level in well 246 rises more deliberately and over a longer period of time in response to an increase in rainfall than the water-level in well 339, so by analogy the water-level in those observation-wells in areas of deep water-table fluctuates still less, with still greater delay, and establishes trends that are still more persistent. The seeming unresponsiveness of water-levels in wells in areas of deep water-table is in no sense proof that recharge does not occur. In fact, the comparison presented above implies that it can and does occur.

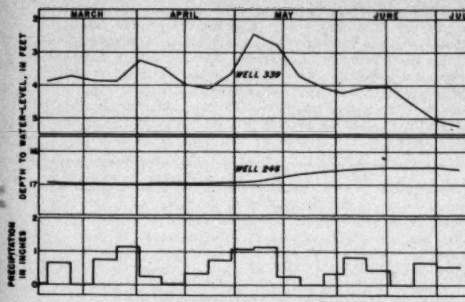


FIGURE 1 — GRAPH OF THE WATER-LEVELS IN TWO WELLS NEAR GRAND ISLAND, NEBR. IN 1931, AND THE WEEKLY PRECIPITATION AT GRAND ISLAND

A somewhat more definitive item of evidence of ground-water recharge in areas of deep water-table is the existence of perched water. So far as is known, perched water is common in the Great Plains, and it is not difficult to obtain general information regarding its local occurrence from well-drillers and owners of wells. In Box Butte County, Nebraska, perched water is known to exist in a few places, but exact knowledge as to its depth is not available. In Keith County, Nebraska, drillers' reports indicate that in many localities perched water is encountered. In some instances, a single well passed through several minor perched zones of saturation. One well is chosen for this discussion because it obtains its water-supply from a perched zone of saturation. The depth of the water-level in it, and in surrounding wells, was measured. Figure 2 [2] shows the location of well 245, which ends at the perched zone of saturation. It is 174 feet deep, and the water-level in July 1935 was about 156 feet below the land-surface. The water-level in the three nearest wells--Nos. 244, 246, and 302--lies at depths of more than 200 feet below ground-surface. The altitude of the measuring points of these wells was determined, and water-table contours with a ten-foot interval were constructed, as shown in the Figure. The water-table in the vicinity of well 245 slopes at a fairly uniform rate toward the northeast, but the water-level in it stands between 50 and 60 feet above the regional water-table. This perched zone of saturation is extremely pertinent to the present argument. In the first place, the perched water in it must of necessity have seeped downward through 156 feet of Ogallala sediments, which fact in itself proves that ground-water recharge occurs in areas of deep water-table. There is no other plausible source of this water. In addition, successive minor zones of perched water reported at different levels in other wells in Keith County strongly suggest that infiltration to the regional zone of saturation may go on deviously, and that obstructions in the zone of aeration are not necessarily effective in preventing recharge. In parts of the Great Plains where the geologic conditions are not so favorable for the existence of perched water as in Keith County, the inference is that water passes to the regional water-table without obstruction.

Figure 2 introduces the third line of evidence, namely, that the water-table in most parts of the Great Plains stands at a higher elevation than the nearby rivers and small streams.

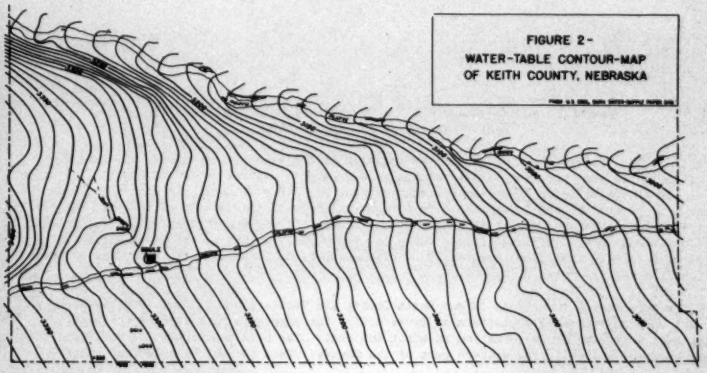


FIGURE 2-
WATER-TABLE CONTOUR-MAP
OF KEITH COUNTY, NEBRASKA

Regionally, the rivers and small streams do not supply the ground-water to the zone of saturation beneath the high upland divides. On the contrary, the ground-water migrates by lateral percolation from the divide-areas toward the perennial water-courses. In Brule Canyon, northwest of the town of Brule, the water-table contours bulge conspicuously downstream. Here must be a local source of concentrated recharge to the zone of saturation. Well 249, situated in about the middle reaches of the canyon where the bulge is strongly developed, encounters water at a depth of 119 feet below the land-surface at that point. It is very probable that such local concentrations of recharge are common in the Great Plains, but it is equally probable that in the plains as a whole they can not be relied upon as a source of all or most of the recharge in upland areas.

A water-table contour-map that is also germane to the present argument is shown in Figure 3 [3]. Here we see contours drawn on the water-table in Box Butte County, Nebraska, with an interval of 50 feet. This area lies just beyond the western edge of the great sandhills region of central and western Nebraska. A narrow extension of the sandhills lies to the south of the County, and the first ranks of sandhills nearly coincide with both the eastern and southern boundaries of the County. The Box Butte table-land occupies the high divide between the Niobrara

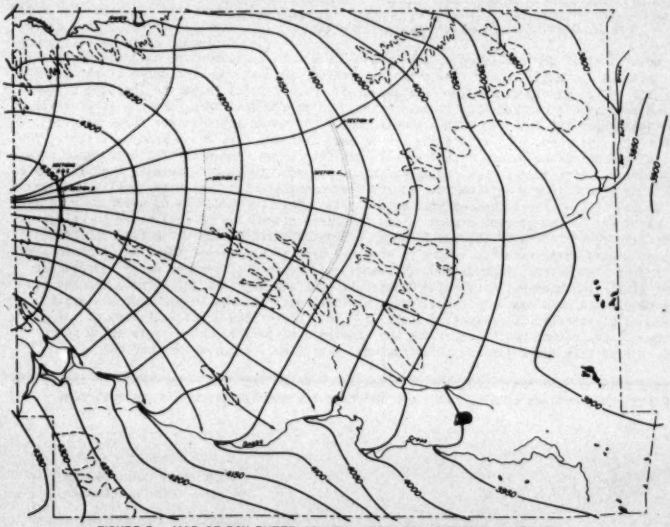


FIGURE 3 — MAP OF BOX BUTTE COUNTY, NEBRASKA, SHOWING CONTOURS AND GRADIENTS OF THE WATER-TABLE

and North Platte valleys, and extends to the westward to the Wyoming State-line, and beyond. Here again we see that the ground-water stands at a greater elevation under the high divide-areas than in the stream-valleys. The flow of both the Niobrara River at the north and Snake Creek at the south is perennial, and is sustained in part by water that percolates down to their valleys from the high divides. At the eastern edge of the County the eastward migration of the ground-water is obstructed by high water-levels under the sandhills. A part of the ground-water is drained by Box Butte Creek, but much of it is discharged by evaporation from lakes, and by transpiration from seepage-areas.

The water-bearing formations in Box Butte County are Tertiary sandstones and siltstones that rest upon an impermeable platform of Brule silt. The aggregate thickness of the water-bearing beds above the Brule formation is about 500 feet. The beds dip toward the east, and the younger beds are absent in the western part of the County. Thus the thickness of the water-

bearing formations increases toward the eastern part of the County, and is least in the western part. Moreover, the water-table slopes to the eastward at a lesser rate than the land-surface, so that as the water-bearing material thickens, relatively more of it is saturated. The water-table in the area in the north-central part of the County that is enclosed within the broken line lies at least 100 feet below the land-surface, but near the western boundary of the County it lies at a depth of more than 250 feet.

The configuration of the water-table contours shown in Figure 3 is most significant. It shows that most of the ground-water that enters the County from the west in the narrow space between the headwaters of Snake Creek and the Niobrara River is diverted toward the Niobrara River and Snake Creek, and does not reach the eastern part of the County. Conversely, little of the water crossing the contours in the east-central part of the County could have originated in the western part of the County. The flow-lines that have been drawn at right-angles to the contours demonstrate this important fact. Now if it is assumed that all of the ground-water that is percolating eastward through the central part of the County entered the County by percolating from the region to the west, then, if other factors remain the same, this flaring-out of the flow-lines should have one of two alternative results, namely, (1) a decrease in the velocity of ground-water movement, or (2) a decrease in the thickness of the zone of saturation above the impermeable platform. Quite certainly neither of these results has been observed. On the contrary, there is a gradual increase in the thickness of saturated material beneath the eastern part of the County than beneath the western part, and the gradient of the water-table remains about constant across the median part of the County, at about 14 or 15 feet to the mile. This being so, then one of two circumstances must account for it, namely, (1) the average permeability of the water-bearing material must undergo a systematic and gradual decline across the County, or (2) much of the ground-water in the central and eastern parts of the County must have as its origin recharge from the land-surface. As for this pair of alternatives, it can be said that all the evidence indicates that the permeability of the successive beds of Tertiary sandstone does not decrease across the County toward the east. It would seem, then, that we have eliminated the logically necessary corollaries of our assumption that the ground-water beneath the upland plain in the central and eastern parts of the County is all derived from percolation from the west. And we therefore conclude that much of the ground-water in those parts of the County is derived from recharge in the upland plain which has reached the water-table through a zone of aeration from 100 to 250 feet thick.

It is not necessary to leave our conclusion in this abstract form. We not only conclude that ground-water recharge takes place, but we can calculate how much recharge takes place. Two cross-sections were selected between a pair of flow-lines, one section being in the western part of the County, and the other being near the central part of the County, down the gradient of the water-table. Owing to the flaring of the flow-lines, the eastern section will be longer than the western section; also, the thickness of saturated material will be greater at the eastern section. The hydraulic gradient is about the same at both sections. If the transmissibility of the material at both cross-sections is about the same, then a great deal more water will be passing through the eastern section of material than through the western. That amount of water by which the quantity of water passing through the western section is exceeded by the quantity passing through the eastern section will represent the ground-water recharge that takes place from the land-surface in the tributary-area between the two cross-sections. The permeability of the Tertiary sandstones was determined from the recovery of a pumped irrigation-well in the western part of the County near the western cross-section. Comparison of the behavior of this well with another near the eastern cross-section gives an indication of the permeability at both sections. The calculations were made according to the following general procedure: The two cross-sections A and A' were chosen to pass through the two irrigation-wells mentioned above, and the first pair of flow-lines chosen as lateral limits were about as far apart as possible. Then as a check, another computation was made by using two other cross-sections, B and B', and a different pair of flow-lines that are nearer together. A third computation was made by using the same cross-section at the west, C, the first pair of flow-lines, but a new eastern cross-section, C', which was located midway between the two cross-sections previously used.

The recharge, calculated from the base-data available, ranges in amount from about 0.75 to slightly more than one inch a year over the tributary-areas between the pairs of cross-sections used. The application of these values of recharge in Box Butte County to the present study serves the purpose of demonstrating that a measurable, and not inconsiderable, amount of water reaches the water-table each year through 100 to 250 feet or more of unsaturated Tertiary alluvial materials.

If we look at the nature of the evidence presented so briefly here, we can see that, although we have no exact information as to the detailed manner in which ground-water recharge

occurs in the upland areas, we nevertheless have the means of speculating on its general character. The water-levels in observation-wells in the high uplands of Nebraska have as yet exhibited no definite upward or downward trend during the five years of measurement. This should mean that ground-water discharge by lateral percolation from the upland areas to points of natural discharge is just about balanced by the recharge in the upland areas. The ground-water discharge by lateral percolation is slow and continuous, and we may conclude that the recharge is accordingly slow and continuous. What, then, is the effect of cycles of drought and wetness upon water-levels in areas of deep water-table? Probably slight declines of the water-level over a period of years that lag behind and outlast the droughty cycles are succeeded by slight rises that lag behind and outlast the wet cycles. If this is true, then recharge in the areas of deep water-table must be continuous, and only slightly and tardily variable.

I wish to acknowledge the help and advice of L. K. Wenzel of the Geological Survey in preparing this paper.

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ON THE FLOW OF WATER IN AN ELASTIC ARTESIAN AQUIFER

C. E. Jacob

Introduction--Slichter showed in 1898 that a solution may be obtained for a given problem in the steady motion of ground-water by solving the familiar Laplace equation and that therefore in steady-state conditions a problem in the motion of ground-water is mathematically analogous to a problem in the steady flow of heat or electricity [see 1 of "References" at end of paper]. More recently it has been recognized that the analogy holds also for the non-steady-state flow of compressible liquids, in elastic systems as well as in rigid systems.

In studying the effect of the discharge of flowing wells on the head in the Dakota sandstone, Meinzer [2, 3] concluded that the water discharged by the wells had largely been derived locally from storage. It was found that the amount of water withdrawn from storage could not be accounted for on the basis of the compressibility of water alone but that it might be accounted for on the basis of the probable compressibility of the sandstone itself. Prior to that time, estimates of water-supplies from artesian aquifers had been based upon the assumption that artesian aquifers are perfectly incompressible and inelastic. However, as Meinzer states [2, p. 289], "artesian aquifers are apparently all more or less compressible and elastic though they differ widely in the degree and relative importance of these properties. In general, the properties of compressibility and elasticity are of the most consequence in aquifers that have low permeability, slow recharge, and high head."

The concept of compressibility and elasticity of artesian aquifers fostered by Meinzer has been extended by Theis [4]. By recourse to the analogy that exists between the laminar flow of water through the interstices of porous materials and the flow of heat through solid media, Theis [5] derived "the relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage." This analogy has as its basis the assumption that owing to elastic compression of the water-bearing beds and the expansion of water confined therein "a specific amount of water is discharged instantaneously from storage as the pressure falls." However, for reasons to be considered presently, it appears that the chief source of the water derived from storage "within" an artesian aquifer is probably the contiguous and intercalated clay beds (or shale-beds, in a sandstone-aquifer) and that because of the low permeability of the clays (or shales) there is a time-lag between the lowering of pressure within the aquifer and the appearance of that part of the water which is derived from storage in those clays (or shales). Such lag-effects are necessarily difficult to handle mathematically. Therefore, in the work which follows it is assumed that the release of the stored water is immediate following the decline of pressure and that the rate at which it is released is directly propor-

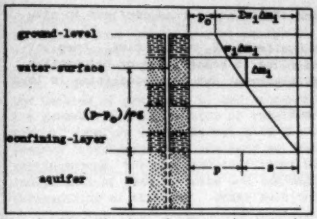

Fig. 1--Distribution of stress in artesian aquifer and overlying beds

tional to the rate of decline of the pressure. The problem is thus reduced to that of flow in an homogeneous elastic artesian aquifer confined between two impermeable planes. These simplifying assumptions are justified because the mathematical solution based thereon appears consistently to yield results that are confirmed by observation.

The writer proposes to derive "from scratch" the fundamental differential equation governing the flow of water in an elastic artesian aquifer, considering in turn each of the assumptions that are necessary to the derivation of the equation. He proposes further to solve the flow-equation for one of the more important cases, that of radial flow in an homogeneous aquifer of uniform thickness and infinite areal extent, thus obtaining the same solution as that derived from the heat-analogy.

Compression of aquifer--The combined weight of the overlying beds and the atmosphere above produces in the aquifer a stress equal to $(p_o + \Sigma w\Delta m)$, where p_o is the atmospheric pressure and where w is the weight of a unit-volume of material in a stratum of thickness Δm (see Fig. 1). This load may be considered as being borne in part by the solid "skeleton" of the aquifer and in part by the water confined therein. By equilibrium of the forces acting on the plane of contact between the aquifer and the confining layer

$$(p_o + \Sigma w\Delta m) = (s + bp) \qquad (1)$$

where s is the compressive stress in the solid part of the aquifer, where p is the hydrostatic pressure within the aquifer, and where b may be considered ideally to represent the proportion of the plane of contact between the aquifer and the confining layer over which the hydrostatic pressure is effective [6]. Actually, of course, there is no aquifer which is bounded sharply by an absolutely impervious confining bed. The factor b merely represents a concept introduced to facilitate mathematical treatment of the problem.

Neglecting for the moment any changes in barometric pressure and delay in subsidence of the overlying beds, the load on the aquifer may be considered to remain constant. Thus $(ds + bdp) = 0$, or $-(ds/dp) = b$. The factor b is thus defined as the negative ratio of a given change in compressive stress to the change in hydrostatic pressure producing it. In an aquifer composed of uncemented granular material the value of b is unity. In a solid aquifer, as a limestone, having tubular channels, b is apparently equal to the porosity. The value of b for a sandstone doubtless ranges between these limits, the exact value depending on the degree of cementation and probably also on the nature of the contact between the sandstone and contiguous shales.

A volume, V, of a given aquifer contains a mass of water, $M = \rho\theta V$, where ρ is the density of the water and θ is the porosity of the material of which the aquifer is composed. Consider a vertical column of the aquifer of cross-section ΔA_z and height m, equal to the thickness of the aquifer. The mass of water contained therein is $\Delta M = \rho\theta m\Delta A_z$. As the hydrostatic pressure is decreased by Δp, the fluid density is decreased by $\Delta\rho$, and the aquifer is compressed an amount Δm, thus decreasing the porosity by $\Delta\theta$. If the pressure declines at a rate $(\partial p/\partial t)$, the mass of water per unit-surface area contained within the elemental volume of aquifer decreases at a rate

$$\partial^2 M/\partial A_z \partial t = \partial(\rho\theta m)/\partial t \qquad (2)$$

The variation of each of the variables ρ, θ, and m may be expressed in terms of the variation of p. As the hydrostatic pressure is reduced, the water contained in the aquifer undergoes elastic expansion, its density being reduced in accordance with

$$d\rho = (\rho/E_w)dp \qquad (3)$$

E_w being the bulk modulus of elasticity of water (approximately 300,000 lbs/in^2 at average ground-water temperatures).

The increase in compressive stress occasioned by the decline in hydrostatic pressure is accompanied by compression of the aquifer, its thickness being decreased by

$$dm = -(m/E_s)ds = (m/E_s)bdp \qquad (4)$$

where E_S is the modulus of compression of the solid skeleton of the aquifer as confined in situ.

The volume of solid material in a given column of the aquifer is $V_S = (1 - \theta/m)A_Z$. Neglecting the change in volume of the solid material in the aquifer due to compression or deformation of the individual particles, and also neglecting lateral displacement due to inequalities in load

$$dV_S = 0 = A_Z[(1 - \theta)dm - md\theta]$$

from which

$$d\theta/(1 - \theta) = dm/m$$

But, from equation (4), $dm/m = bdp/E_S$, therefore

$$d\theta = (1 - \theta)bdp/E_S \tag{5}$$

The pressure at a point of elevation z within the aquifer is $p = [p_0 + \rho g(h - z)]$, where p_0 is the atmospheric pressure, as before, and where h is the "head", or elevation of the free water-surface in a well penetrating the aquifer to the point in question. The elevation of the water-level in a well is ordinarily determined by tape-measurement of the depth to water below a "measuring point" of known elevation and is referred to mean sea-level or some other arbitrary datum, as is z also. In considering purely radial flow in an horizontal aquifer, z may be taken as constant. Then, neglecting fluctuations in atmospheric pressure, $dp = \rho g dh$, and equations (3), (4), and (5) become, respectively,

$$d\rho = (\rho/E_W)\,\rho g dh \tag{6}$$

$$dm = (bm/E_S)\,\rho g dh \tag{7}$$

$$d\theta = [(1 - \theta)b/E_S]\,\rho g dh \tag{8}$$

Substituting in equation (2) the values of $d\rho$, dm, and $d\theta$ given by equations (6), (7), and (8), and reducing

$$\partial^2 H/\partial A_Z \partial t = \rho[\rho g \theta m(1/E_W + b/\theta E_S)](\partial h/\partial t) \tag{9}$$

In equation (9) the quantities ρ, θ, and m are considered to represent initial values. It is assumed also that E_W and E_S remain constant over the range of pressure-changes involved. As z is one of the independent variables, $(\partial z/\partial t) = 0$, and $(\partial p/\partial t) = \rho g(\partial h/\partial t)$. Thus the previous restriction that the aquifer be horizontal is removed.

Coefficient of storage--The quantity enclosed in brackets in equation (9) is found by inspection to be dimensionless. This factor is identical to the "coefficient of storage" of Theis [5, p. 894]. It is designated by the letter S. That is,

$$S = \rho g \theta m(1/E_W + b/\theta E_S) \tag{10}$$

Equation (9) thus becomes

$$\partial^2 H/\partial A_Z \partial t = \rho S(\partial h/\partial t)$$

by which the coefficient of storage is given as

$$S = (1/\rho A_Z)(dH/dh) \tag{11}$$

that is, assuming there is no lag in the release of stored water, or in other words that S is independent of the variable t.

The coefficient of storage is defined by equation (11) as the volume of water of a certain density released from storage within the column of aquifer underlying a unit-surface area during a decline in head of unity. This definition conforms to that given by Theis. The coefficient of storage is presumably a constant which may be determined empirically for a given aquifer from data on the decline of head produced by pumping from wells penetrating the aquifer.

In equation (10) the storage derived from expansion of the confined water is given by $(g\theta m/E_W)$, corresponding to the $(1/E_W)$ in parentheses. The storage derived from compression of

the aquifer is given by the remainder, which is represented by the other term in parentheses, $(b/\theta E_s)$. These two terms account for all the water derived from storage within an hypothetical elastic artesian aquifer bounded by impermeable planes. In the actual case, however, a third term is required to account for the water derived from storage in the adjacent and included clay-beds. This term would in general be a function of the rate and perhaps also the magnitude of the decline of pressure, of the thickness and distribution of the intercalated clay-beds, and of the permeability and modulus of compression of the clay; but under ordinary conditions, of course, equation (9) would not hold true. However, if there are a sufficient number of clay-laminae interbedded with the sand so that the release of stored water from the clay is virtually instantaneous, the required additional term may, for all practical purposes, be considered to be independent of both the rate and the magnitude of the decline of pressure and independent of the permeability of the clay. Under such conditions the coefficient of storage may be given as

$$S = \rho g \theta m (1/E_w + b/\theta E_s + c/E_c) \qquad (12)$$

where E_c is the modulus of compression of the clay and where c is a dimensionless quantity that depends largely on the thickness, configuration, and distribution of the intercalated clay-beds.

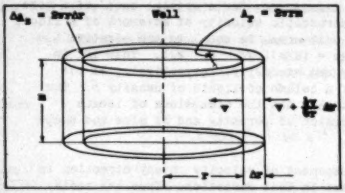

Fig. 2--Radial flow through concentric cylindrical surfaces

Equation of continuity--The time-rate of change of the mass of liquid per unit-volume contained in the elemental volume $\Delta V = m\Delta A_z$, is

$$\partial^2 M/\partial V \partial t = (1/m)\partial^2 M/\partial A_z \partial t = (\rho S/m)(\partial h/\partial t) \qquad (13)$$

According to the law of conservation of matter this must equal the net flux per unit-volume across the boundaries of the same volume-element. In the case of radially symmetrical flow, as occurs in the vicinity of a single well pumping from an homogeneous aquifer of constant thickness, and with which we are primarily concerned here, the volume-element to be considered is that bounded by two cylindrical surfaces, of radii r and $(r + \Delta r)$, respectively, and by the upper and lower bounding planes of the aquifer, as indicated in Figure 2.

The flux through the inner cylindrical surface is $\rho A_r v$, where $A_r = 2\pi rm$ is the area of the surface, and where v is the radial velocity, considered positive when the motion is away from the origin. Similarly, the flux through the outer cylindrical surface is $(\rho + \Delta\rho)(A_r + \Delta A_r)(v + \Delta v)$. Neglecting differentials of higher order, the net inward flux through the bounding surfaces of the volume considered is

$$\Delta M_r/\Delta t = -\rho A_r v(\Delta\rho/\rho + \Delta A_r/A_r + \Delta v/v)$$

[The leakage from or into the overlying and underlying beds has been neglected. Change in the rate of leakage accompanying the decline in head is accounted for approximately by the third term in parentheses in equation (12).]

Considering in turn each of the terms of the right-hand member of the foregoing equation

$$\begin{cases} \Delta\rho/\rho = (\delta p/\delta r)\Delta r/E_w \\ \Delta A_r/A_r = \Delta r/r + (\delta m/\delta r)\Delta r/m \\ \Delta v/v = (\delta v/\delta r)\Delta r/v \end{cases}$$

For the range of pressure-gradients ordinarily occurring in ground-water bodies, $(\delta p/\delta r)\Delta r/E_w$ is certainly negligible in comparison with $\Delta r/r$. And, since $dm/m = bdp/E_s$, the quantity $[(\delta m/\delta r)\Delta r/m]$ also may be considered negligible, leaving

$$\Delta M_r/\Delta t = -\rho A_r v[\Delta r/r + (\delta v/\delta r)\Delta r/v]$$

Passing to differentials, the net flux per unit-volume is

$$(1/2\pi rm)\partial^2 M_r/\partial r \partial t = -\rho[v/r + (\partial v/\partial r)] \qquad (14)$$

From equation (13) the time-rate of change of the mass of liquid per unit-volume contained in the element whose volume is $\Delta V = m\Delta A_z = 2\pi rm\Delta r$ is

$$(1/2\pi rm)\partial^2 H/\partial r\partial t = (\rho S/m)(\partial h/\partial t) \qquad (15)$$

Equating the right-hand members of equations (14) and (15) it is found that in accordance with the law of conservation of matter

$$(v/r + \partial v/\partial r) = -(S/m)(\partial h/\partial t) \qquad (16)$$

Equation (16) is a combination of two equations: The "equation of continuity," which alone expresses the law of conservation of matter, and the "equation of state," which expresses the relation between the fluid density and the pressure, the temperature being considered constant. Equation (3) is the equation of state in differential form.

Darcy's law and permeability--The variable v may be eliminated from equation (16) by introducing a further relation known as Darcy's law. This is so named in honor of H. Darcy, who in 1856 found that the rate at which water flows vertically downward through a sand-filter (discharging at atmospheric pressure) is directly proportional to the sum of the thickness of the bed of sand and the depth of water covering it and inversely proportional to the thickness of the bed, the constant of proportionality being a coefficient which depends on the nature of the sand [7]. The principle enunciated by Darcy is but an expression, for a special case, of a more generalized law which may be stated as follows: The macroscopic velocity of movement of a liquid through a permeable medium, that is, the discharge per unit-area, is equal to the negative gradient of a potential which is defined by $\varphi = (k/\mu)\rho gh = (k/\mu)(\rho gz + p - p_0)$. That is, in vector form, $\overline{v} = -$ grad φ. Here ρ and μ are the density and viscosity, respectively, of the fluid in question; h is the head, expressed in terms of a column of liquid of density ρ. The constant k is independent of the properties of the fluid and has the dimensions of length squared. It characterizes the flow-medium, being a function of porosity and of size and shape of grain, etc.

It follows from the foregoing equation that the component of velocity in any direction is equal to the negative component of the potential-gradient in that direction. Thus the radial component of the velocity-vector is

$$v = -(\partial\varphi/\partial r) = -(\rho gk/\mu)(\partial h/\partial r) \qquad (17)$$

Flow away from the origin is considered positive, hence the negative sign in equation (17). Combining the constants k and g and the quantities ρ and μ, the latter two also being assumed constant,

$$v = -K(\partial h/\partial r) \qquad (18)$$

where

$$K = \rho gk/\mu \qquad (19)$$

The factor K, known as the "permeability", has the dimensions of length divided by time, or velocity, and is here expressed in the usual velocity-units, that is, in ft/sec. However, it is not to be confused with the macroscopic velocity of movement of the fluid. Actually the permeability is equal to the discharge per unit-area which would obtain under unity hydraulic gradient. The cgs equivalent of K is Muskat's $\overline{k}$, which he terms "the 'effective' permeability for the composite system of porous medium and liquid" [8, p. 72].

For all practical purposes, K may be considered constant for a given homogeneous isotropic aquifer transmitting water at normal ground-water temperature. If the aquifer is not homogeneous and isotropic, the value of the permeability, K, will in general be affected more by the variation of k from place to place within the aquifer than by the variation of any one of the other three factors ρ, μ, and g. Under gradients normally encountered in ground-water bodies the variation of density is negligible, as previously shown. The variation of viscosity with pressure is likewise negligible. And, although both the density and the viscosity vary with the temperature, the variation of the temperature of the water in a given aquifer, both in time and in space, is in most cases so slight that these two factors may be considered constant. However, it should be pointed out that in attempting to effect a direct comparison between values of average permeability determined for different aquifers in the field and values of permeability determined in the laboratory, corrections should be applied for the variation of viscosity with temperature. (Temperature-corrections for density as well as pressure-corrections for both density and viscosity may be omitted. Also, variation in the acceleration of gravity from locality to locality may be neglected without serious consequence.) If, following the convention

of Meinzer, 60° F is taken as the standard temperature, the value of permeability corrected for temperature is $K_{60} = (\mu/\mu_{60})K$, where μ_{60} is the viscosity of water at 60° F, and where μ is the viscosity of water at the temperature at which the value of K was determined, whether in the laboratory or in the field.

The coefficient of permeability adopted by the Geological Survey, denoted here by P_{60}, is defined as the rate of flow of water at 60° F, in gallons a day, through a square foot of cross-section, under unity hydraulic gradient [9]. Thus, $P_{60} = 646{,}000\ K_{60}$, one cubic foot per second being approximately equivalent to 646,000 gallons per day.

Integration of fundamental differential equation--Substituting the value of v given by equation (18) in equation (16) and multiplying both members of the equation by $(-r^2/K)$,

$$r(\partial h/\partial r) + r^2(\partial^2 h/\partial r^2) = (r^2 S/Km)(\partial h/\partial t) \tag{20}$$

This is the fundamental differential equation for the flow of a compressible viscous liquid in an elastic artesian aquifer. The particular solution of this equation which satisfies the necessary boundary-conditions is the equation of the piezometric surface, its elevation, h, being expressed as a function of the independent variables r and t, and the constants K, m, and S.

The first integration may be performed by inspection. For, assume

$$r(\partial h/\partial r) = -2c\, e^{-r^2 S/4Kmt} \tag{21}$$

Then

$$r^2(\partial^2 h/\partial r^2) = 2c\, e^{-r^2 S/4Kmt} + c(r^2 S/Kmt)e^{-r^2 S/4Kmt}$$

and

$$r(\partial h/\partial r) + r^2(\partial^2 h/\partial r^2) = (r^2 S/Km)(c/t)e^{-r^2 S/4Kmt}$$

Thus, according to equation (20)

$$(\partial h/\partial t) = (c/t)e^{-r^2 S/4Kmt} \tag{22}$$

By differentiating both sides of equation (22) with respect to r and integrating with respect to t, properly evaluating the constant of integration, the same value is obtained for $(\partial h/\partial r)$ as that given by equation (21). Thus equation (21) is shown to be a particular (partial) solution of the differential equation. The differentiation is performed as follows:

$$\partial^2 h/\partial t \partial r = (c/t)(-2rS/4Kmt)e^{-r^2 S/4Kmt} = (-2c/r)(r^2 S/4Kmt^2)e^{-r^2 S/4Kmt}$$

Integrating the foregoing equation with respect to t

$$(\partial h/\partial r) = (-2c/r)e^{-r^2 S/4Kmt} + c_1$$

The constant c_1 may be evaluated by a consideration of the boundary-conditions. Assuming the aquifer to be infinite in areal extent, the limit of $(\partial h/\partial r)$ is zero as r approaches infinity, and as the limit of $(1/r)e^{-r^2 S/4Kmt}$ is also zero as r approaches infinity, c_1 must equal zero. Thus

$$(\partial h/\partial r) = (-2c/r)e^{-r^2 S/4Kmt} \tag{23}$$

which, on multiplying through by r, becomes identical to equation (21).

The other boundary-condition, namely, that the initial distribution of head is uniform throughout, was satisfied by the original assumption [equation (21)]. For, when $t = 0$ $e^{-r^2 S/4Kmt} = 0$, and hence $(\partial h/\partial r) = 0$.

The value of c may be determined by substituting the proper values of $(\partial h/\partial r)$ and $(\partial h/\partial t)$ in the equation

$$Q = -2\pi r m K(\partial h/\partial r) + \int_0^r S(\partial h/\partial t)\, 2\pi r\, dr \tag{24}$$

This equation is a statement of the fact that the discharge of the well is equal to the sum of the flow through a cylinder of variable radius, r, and the increase in rate of flow proceeding toward the well caused by compression of the volume of aquifer enclosed by the cylinder. The discharge through the cylindrical surface is $A_r v = -2\pi rm\ K\ (\partial h/\partial r)$, and the gain in rate of flow due to compression is $\int S\ (\partial h/\partial t)\ dA_z = \int_0^r S\ (\partial h/\partial t)\ 2\pi r dr$. The significance of the lower limit zero is that the radius of the well is considered negligible.

Making the proper substitutions in equation (24) and performing the integration indicated, it is found that $Q = 4\pi cKm$, from which

$$c = Q/4\pi Km \tag{25}$$

Dimensional analysis applied to the factor c yields the following: $[L^3/T]/[L/T][L] = [L]$. In other words, c has the dimensions of length. [This c is not to be confused with that in equation (12).] Inasmuch as the aquifer is assumed to be homogeneous and uniform in thickness, K and m are constant. Therefore, since c is constant, Q must also be constant.

Let $r^2S/4Km = b$. This quantity [not to be confused with $b = -(ds/dp)$] has the dimensions of time. That is, $[L^2]/[L/T][L] = [T]$. Equation (22) may now be rewritten as

$$(\partial h/\partial t) = (c/t)\ e^{-b/t} \tag{26}$$

This equation may be integrated to give h in terms of b, c, and t. In dimensionless form,

$$h/c = \int_0^t (1/t)e^{-b/t}dt$$

where the upper limit of integration is the time elapsed since beginning pumping at a constant rate. By arbitrarily choosing the initial piezometric surface as the plane of reference--that is, the plane to which h is referred--a constant factor, which would ordinarily appear in the left-hand member of the equation, is thereby eliminated.

Let $b/t = u$. Then $t = b/u$, and $dt = (-b/u^2)du$. To determine the new limits of integration: when $t = 0$, $u = \infty$; and when $t = t$, $u = b/t$. Making these substitutions

$$h/c = \int_\infty^{b/t} (u/b)e^{-u}(-b/u^2)du$$

That is,

$$h/c = \int_{b/t}^\infty (e^{-u}/u)du \tag{27}$$

This integration may be performed by parts as follows:

$$\int(e^{-u}/u)du = \int(1/u)du + \int[(e^{-u} - 1)/u]du$$

The first integral yields $\log_e u$. The quantity under the second integral sign may be expanded as

$$(e^{-u} - 1)/u = -1 + u/2! - u^2/3! + u^3/4! - \ldots + (-1)^n u^{n-1}/n!$$

As this series converges uniformly for all values of u, it may be integrated term by term, giving

$$\int[(e^{-u} - 1)/u]du = -u + u^2/2\cdot 2! - u^3/3\cdot 3! + u^4/4\cdot 4! - \ldots + (-u)^n/n\cdot n!$$

By properly evaluating the integral for the upper and lower limits of integration the following solution is obtained:

$$h/c = -0.5772 - \log_e u + u - u^2/2\cdot 2! + u^3/3\cdot 3! - u^4/4\cdot 4! + \ldots + (-u)^n/n\cdot n! \tag{28}$$

in which b/t has been replaced by u corresponding to the fixed value of t, which, however, may now be considered variable. The constant 0.5772····· is known as Euler's constant.

It should be noted that equation (28) is in dimensionless form. The solution given by this equation is the same as that derived by Theis [5] and by Muskat [8, p. 667] by recourse to the heat analogy. The integral

$$Ei(b/t) = \int_\infty^{-b/t} (e^{-u}/u)du \tag{29}$$

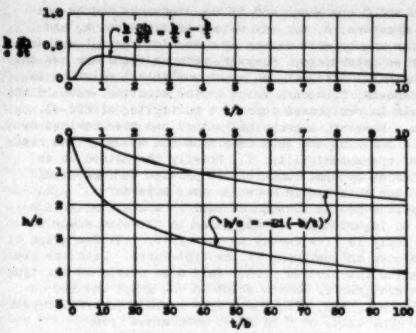

Fig. 3--Theoretical drawdown curves

is known as the "exponential integral." Values of this function have been published in tabular form [10] for a limited range of values of the argument and are reproduced in part by Theis [4].

In terms of the exponential integral, then, the drawdown is given in the following dimensionless form

$$(h/c) = - Ei(-b/t) \qquad (30)$$

Figure 3 is a graph of this equation. The abscissas are (t/b), the scale along the upper margin of the graph applying to the upper curve and that along the lower margin to the lower curve. The ordinates are (h/c). The two curves shown in Figure 3 are typical "drawdown curves." Inasmuch as they are in dimensionless form, they are typical of all such curves that might be obtained under the postulated conditions.

Initially the slope of the drawdown curve is zero, and up to a certain point as (t/b) increases the slope also increases. Thereafter, however, the slope decreases continuously as (t/b) increases. It is noted that the maximum slope of the drawdown curve occurs at (t/b) = 1, that is, when $t = r^2S/4Km$. This is also seen from the graph of the equation $(b/c)(\partial h/\partial t) = (b/t)e^{-b/t}$, which also is given in Figure 3. At the point (t/b) = 1, (h/c) = -Ei(-1) = 0.219, and $(b/c)(\partial h/\partial t) = e^{-1} = 0.368$. It is interesting to note also that the value of the drawdown at the time of occurrence of the maximum rate of decline of the head is the same for all values of r. For, according to the above, at this point h = 0.219 c = 0.219 Q/4πKm.

The drawdown may also be expressed in dimensionless form in terms of the distance, r, and an additional parameter, a, which has the dimensions of length. That is,

$$(h/c) = -Ei(-r^2/a^2) \qquad (31)$$

where $a^2 = (4Kmt/S)$, or where $(r^2/a^2) = (r^2S/4Kmt) = (b/t)$.

Figure 4 is a graph of equation (31). The abscissas of the upper curve are given on the upper margin of the graph. Similarly, the abscissas of the lower curve are given on the lower margin. These two curves are typical half-sections of the so-called "cone of depression." As (r/a) becomes infinite, (h/c) approaches zero, satisfying the postulated infinite areal extent of the aquifer. As (r/a) approaches zero, (h/c) theoretically becomes infinite. Practically, however, h is limited to the drawdown at the well-face, corresponding to the theoretical value of drawdown at a distance $r = r_w$, where r_w is the "effective radius" of the well.

Determination of coefficients of storage and transmissibility by graphical method--Equation (30), or equation (31), may be rewritten as

$$h = -(114.6\ Q/T)[Ei(-1.87r^2S/Tt)] \qquad (32)$$

where Q is the pumping rate in gallons a minute; t is the time elapsed since the beginning of pumping, in days; and T is the "coefficient of transmissibility" of Theis, which he defines [4, p. 894] as "the number of gallons of water which will move in one day through a vertical strip of the aquifer one foot wide and having the height of the aquifer when the hydraulic gradient is unity. It is the average coefficient of permeability, adjusted for the temperature, multiplied by the thickness of the aquifer in feet."

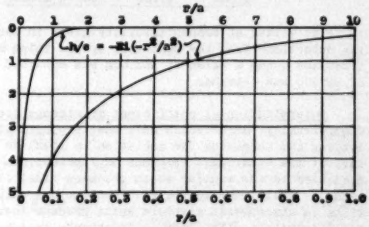

Fig. 4--Theoretical half-sections of cone of depression

It is seen from equation (32) that if S and T are known and if the discharge can be measured, it is then possible to determine the drawdown, h, for any values of distance, r, and time, t. Conversely, if h can be measured for one or more values of r and for several values of t and if the discharge is known, S and T may be determined. However, because there are two unknowns and because of the nature of the exponential integral, an exact analytical solution is not possible. And inasmuch as one of the unknowns, T, occurs twice in the equation, once in the argument of the exponential integral and again in reciprocal form as a multiplier of Ei(-u), solution by trial is rendered very laborious. However, a graphical method has been devised by Theis [11] whereby it is possible to effect a solution and thus determine the value of the coefficient of storage, S, and the coefficient of transmissibility, T. Briefly the method is as follows: (1) Values of -Ei(-u) taken from tables of that function are plotted on logarithmic coordinates against values of u. The curve thus obtained is known as the "type-curve." (2) Values of drawdown, h, obtained from observations of the decline of head in the vicinity of a discharging well are plotted against (r^2/t) on logarithmic tracing paper to the same scale as that used for the type-curve. A convenient scale is five inches to the cycle. (3) The graph of the data plotted on tracing paper is superimposed on the graph of the type-curve. With the axes parallel, a position is found by trial for which the plotted points fall most nearly on the type curve. (4) Then, from the coordinates of an arbitrarily chosen point on one graph and the coordinates of the corresponding point on the other graph, with the graphs in that particular position, the parameters S and T are determined. The value of T is first determined from $T = 114.6\, Q[-Ei(-u_1)]/h_1$. Then, using this value of T the value of S is determined from $S = Tu_1/1.87(r^2/t)_1$. Here u_1 and $-Ei(-u_1)$ are the coordinates of the arbitrarily chosen point on the graph of the type-curve and $(r^2/t)_1$ and h_1 are the coordinates of the corresponding point on the graph of the observational data.

In Table 1 are given values of S and T obtained by application of this method to data from a pumping test conducted at Rockaway Park, Long Island, New York, May 18 to 22, 1939. In the course of construction of well Q 1,030 for the City of New York, a four-inch screen was set in the Lloyd sand between depths of 734 feet and 798 feet below the rotary-table. According to the driller's log there is an 85-foot bed of water-bearing sand between depths of 715 and 800 feet. Well Q 1,030 was pumped for four days at an average rate of 310 gallons a minute. Continuous records were obtained of the decline of water-level in wells Q 288, Q 543, Q 544, and Q 546 nearby. These wells are located on a barrier beach about 2,000 feet wide which separates Jamaica Bay from the Atlantic Ocean. A recording tide-gage was maintained in operation on Jamaica Bay in order to correct the water levels for tidal fluctuations. The ratio between the magnitude of the fluctuations of the water-level in the wells and the actual fluctuations in tide producing them was found to be about 44 per cent for wells Q 543, Q 544, and Q 546, and about 42 per cent for well Q 288. This factor is termed the "tidal efficiency."

Table 1--Coefficients of storage and transmissibility obtained by application of graphical method to pumping test-data

Well	Distance from well Q 1,030, r (feet)	Approximate range of r^2/t (ft^2/sec)	Coefficient of storage, S	Coefficient of transmissibility, T (gpd/ft)
Q 546	67	0.01 to 0.4	1.90×10^{-4}	106,000
Q 543	262	0.2 to 6		
Q 544	313	0.3 to 8		
Q 288	4,100	60 to 1,000	8.0×10^{-4}	114,000

The values of transmissibility given in Table 1 check within reason values of transmissibility determined from the same test by the Thiem method [12]. Using the combination of wells Q 543 and Q 546 a value of 103,000 was obtained for T, and using wells Q 544 and Q 546 a value of 95,000 was obtained.

Determination of coefficient of storage from tidal efficiency or barometric efficiency--Theoretically, an artesian well that exhibits tidal fluctuations, which are due to the alternate loading and unloading (or variation in load) on the confining layer occasioned by the rise and fall of the tide, also responds to fluctuations in atmospheric pressure. That is, the same mechanism in the aquifer which produces tidal fluctuations also produces "barometric fluctuations." Again, the barometric fluctuations observed in a well are proportional to the variations in atmospheric pressure which produce them, the constant of proportionality being termed the "barometric efficiency." It appears that barometric and tidal fluctuations may be taken as an index of the elasticity of the aquifer, and further that in the hypothetical case there is a direct relation between the tidal efficiency or the barometric efficiency and the coefficient of storage.

Consider an homogeneous elastic artesian aquifer which is uniform in thickness and infinite in areal extent. Assume that the aquifer is overlain by beds of uniform thickness which are covered by an equally extensive body of tide-water in which the variations in level occur simultaneously and uniformly throughout. Assume further that variations in atmospheric pressure are likewise uniform over the entire aquifer. Under these conditions, tidal and barometric fluctuations of the head in the aquifer will be uniform and there will be no lateral movement of water. (Non-uniform conditions of loading produce inequalities in head which in turn cause lateral movement of the water confined in the aquifer. And, as a result of the inevitable loss of head accompanying the movement of water, a reduction in the magnitude of the fluctuations occurs.)

Equation (1) is a statement of the condition of equilibrium of pressures on the plane of contact. The term $\Sigma w\Delta m$ may now be considered to include the tide-water in addition to the beds overlying the aquifer. Neglecting for the moment any variation in the surface-level of the body of tide-water, that is, putting $\Sigma w\Delta m$ = constant

$$\Delta p_0 = (\Delta s + b\Delta p) \tag{33}$$

As the atmospheric pressure changes by an amount Δp_0 the water-level in a well penetrating the aquifer fluctuates $-(B\,\Delta p_0/\rho g)$ feet, where B is the barometric efficiency of the well. Thus the net change in hydrostatic pressure within the aquifer is

$$\Delta p = \Delta p_0 - B\Delta p_0 = (1 - B)\Delta p_0 \tag{34}$$

Combining equations (33) and (34)

$$\Delta p = (1 - B)(\Delta s + b\Delta p)$$

from which

$$\Delta p/\Delta s = (1 - B)/[1 - b(1 - B)] \tag{35}$$

When the aquifer and the contained water are compressed by an extensive uniform load, such as represented by an increase in the weight of the atmosphere postulated above, the decrease in volume of water, ΔV_w, is equal to the decrease in volume of aquifer, ΔV. Thus $(\Delta V_w/V_w) = (\Delta V/\theta V)$. It is assumed here that the bulk compression of the individual particles composing the flow-medium is negligible and that there is no leakage from or into contiguous beds. Then, as $(\Delta V_w/V_w) = (-\Delta p/E_w)$ and $(\Delta V/V) = (-\Delta s/E_s)$, it follows that $(\Delta p/E_w) = (\Delta s/\theta E_s)$, from which

$$(\Delta p/\Delta s) = (E_w/\theta E_s) \tag{36}$$

Thus, from equation (35)

$$E_w/\theta E_s = (1 - B)/[1 - b(1 - B)] \tag{37}$$

from which

$$B = 1 - (E_w/\theta E_s)/(1 + bE_w/\theta E_s) \tag{38}$$

Similarly, it may be shown that the tidal efficiency is given by

$$C = (E_w/\theta E_s)/(1 + bE_w/\theta E_s) \tag{39}$$

In other words

$$(B + C) = 1 \tag{40}$$

When b = 1, as for an aquifer composed of an uncemented granular material, such as a quartz-sand,

$$B = 1/(1 + E_w/\theta E_s) \tag{41}$$

and from equation (10)

$$S = (\rho g\theta m/E_w)(1 + E_w/\theta E_s) \tag{42}$$

Thus, for b = 1,

$$S = (\rho g\theta m/E_w)(1/B) \tag{43}$$

The average value of the tidal efficiency, C, for wells Q 543, Q 544, and Q 546 is 0.44. Thus $(1/B) = (1 + E_w/\theta E_s) = [1/(1 - C)] = 1.79$. The average temperature of water in the Lloyd sand is about 65° F. At that temperature the value of $(E_w/\rho g)$ is approximately 300,000 x 144/62.4 = 690,000 feet. According to the log of well Q 1,030 the thickness of the aquifer, m, is 85 feet. Assuming the porosity, θ, to be 35 per cent, $S = (0.35 \times 85/690,000) 1.79 = 4.3 \times 10^{-5} \times 1.79 = 7.7 \times 10^{-5}$. Similarly, for well Q 288, $[1/(1 - C)] = 1.72$, and $S = 7.4 \times 10^{-5}$.

The tidal efficiency was used to compute the theoretical coefficient of storage because it was more easily determined than the barometric efficiency. In fact, it was not found possible accurately to determine B directly from the data at hand. However, the water-level graphs corrected for tidal fluctuations in the ratio of C and for barometric fluctuations in the ratio of (1 - C) showed no residuals that might be correlated with fluctuations in atmospheric pressure, thus confirming in a way the supposed complementary relation between B and C.

The values of coefficient of storage determined from the tidal efficiency are smaller than the corresponding values of coefficient of storage obtained from the pumping test, in one case by more than one order of magnitude. In order to effect an agreement between a value of S given in column (4) of Table 2 and the corresponding value given in Table 1, the value of (cE_w/E_c) given in column (5) is to be added to the value of $(1 + E_w/\theta E_s)$ given in column (3) and multiplied by $(\rho g \theta m/E_w)$, equal to 4.3×10^{-5}, in accordance with equation (12). For example, from the data for well Q 288, $S = (\rho g \theta m/E_w)[(1 + E_w/\theta E_s) + cE_w/E_c] = 4.3 \times 10^{-5}(1.72 + 16.9) = 4.3 \times 10^{-5} \times 18.6 = 8.0 \times 10^{-4}$.

Table 2--Coefficient of storage computed from tidal efficiency

Well	Tidal efficiency, C	$(1 + E_w/\theta E_s)$	Coefficient of storage, S	(cE_w/E_c)
(1)	(2)	(3)	(4)	(5)
Q 546, Q 543, Q 544	0.44	1.79	7.7×10^{-5}	2.63
Q 288	0.42	1.72	7.4×10^{-5}	16.9

According to the data for well Q 288, the amount of "storage" derived from compression of the aquifer and the adjacent and included clay-beds is about 17.6 (that is, 0.72 + 16.9) times as great as the amount derived from expansion of the water; and, according to the data for the other three wells, the amount derived from compression of the aquifer and the adjacent and included clay-beds is about 3.4 (that is, 0.79 + 2.63) times as great as the amount derived from expansion of the water. The determination of the theoretical value of the coefficient of storage from the tidal efficiency (see Table 2) is based on the assumption that "there is no leakage from or into contiguous beds." However, leakage actually does occur, not only from (or into) contiguous beds, but also from (or into) intercalated beds of clay. Therefore, it is not possible to distinguish between that part of the storage derived from compression of the sands and that part derived from compression of the clays. Nevertheless, assuming that all the water derived from storage in the Lloyd sand has been adequately and correctly accounted for, the ratios between the amounts derived from compression of the sands and clays combined and the amounts derived from expansion of the water are as given above.

Flow of compressible fluid in rigid system--The non-steady-state flow of a compressible fluid in a permeable medium has been analyzed by Muskat [8, pp. 621-676] apparently on the assumption that the medium is rigid. He expresses the argument of the exponential integral, used to describe the "transient" effect of a "permanent source" as $-(f\beta\mu r^2/4kt)$; where f is the porosity, identical to θ; where β is the compressibility of the fluid, equivalent to the reciprocal of the bulk modulus, E_w, in atmospheres; and where μ, k, r, and t (in cgs units) have the same meaning as they have here, except that the pressure-factor in k is expressed in atmospheres. Changing the notation to conform to that adopted herein, equating the above to $-u = -(r^2S/4Kmt)$, and substituting for K the value given by equation (19)

$$-\theta\mu r^2/4E_w kt = -\mu r^2 S/4\,gkmt$$

By canceling like quantities in both members of the above equation and solving for S there is obtained the relation $S = (\rho g \theta m/E_w)$, whereas, according to equation (12),

$$S = (\rho g \theta m/E_w)(1 + bE_w/\theta E_s + cE_w/E_c)$$

In other words, it would appear that consideration has been given only to the compressibility of the fluid, and that the compressibility of the fluid medium has tacitly been neglected. Perhaps in some instances the nature, depth, and configuration of oil-producing structures is such that the amount of compaction accompanying decline of pressure is negligible, in which case the compressibility of the fluid media need not be considered. However, it is believed that oil-bearing structures generally are compressible. The subsidence which occurs in oil-fields may be taken as evidence of the compressibility. Where subsidence has not become visually perceptible its occurrence might be definitely established by differential leveling. Incidentally, it seems that in selecting and establishing bench-marks for precise leveling in areas likely to be affected by the reduction of pressure in oil-reservoirs or in artesian aquifers consideration ought to be given to the possibility of subsidence occurring in those areas.

The production of 500 million barrels of oil from an East Texas oil-field having an estimated total fluid content of 7×10^9 barrels, with a drop in reservoir-pressure of only about 375 pounds per square inch, is attributed by Muskat [8, pp. 644-653] to the "drive" exerted on the oil by the water in the Woodbine sand adjacent to the field, which expands as the pressure is lowered. If the production of oil from this field were to be attributed entirely to expansion of the oil itself, there would be required a compressibility 20 times that actually determined for the oil with its dissolved gas. As the oil is known to be undersaturated at the prevailing reservoir-pressure, such a high value of compressibility could not be justified. In accounting for the production on the basis of the expansion of the water alone, the effective compressibility of the water had to be taken as 12 times that of gas-free water. This abnormally high compressibility "may be explained," Muskat says [8, p. 652] "on the assumption that there are gas pockets dispersed through the water-horizon to the extent of 4.9 per cent of the total pore-volume of the sand." However, it appears from the foregoing discussion that the high effective compressibility assumed for the water in the Woodbine sand might more easily be accounted for as representing not only the compressibility of the water, but also the compressibility of the sand, and, more important perhaps than that, the compressibility, in part, of the adjacent and included clay-beds.

According to the few data available, the Lloyd sand, with the water that it contains, appears to be from about 3.4 to 17.6 times as compressible as water alone. The latter figure is probably more nearly the correct value, because the relative amount of compression of the aquifer accompanying a given decline in pressure, as indicated by the value of the coefficient of storage, is small for small values of the ratio between the lateral distance (r, in Table 1) and the depth to the aquifer (715 feet). This is because the virtual load on the aquifer is decreased in the immediate vicinity of the pumped well owing to the lateral strength of the overlying beds, and as a consequence the value of the compressive stress in the skeleton of the aquifer for a given value of hydrostatic pressure is less than it would be if the full weight of the overlying beds rested continually on the aquifer. It is believed that in the case of the Lloyd sand a greater part of the high apparent compressibility is to be attributed to the clays than to any gas that might be trapped in the aquifer. It seems likely that this might apply also to the Woodbine sand, which, with the water (and gas) that it contains, is apparently about 12 times as compressible as water alone.

Actually the procedure followed by Muskat, wherein the "apparent" compressibility of the fluid is adjusted empirically on the basis of the observed pressure-distributions, is in effect equivalent to that of the graphical method outlined on a previous page, although explanations given for the abnormally high compressibility differ. Of course, there remains the possibility that pockets of gas are present in some artesian aquifers, and that therefore they contribute to the high "effective" compressibility of those composite systems of solid and fluid. However, there is no direct evidence of the presence of undissolved gas in any great proportion in the Lloyd sand. It seems likely that an amount of included gas as great as 4.9 per cent of the total pore-volume of the sand would appreciably diminish the tidal fluctuations. As previously indicated, tidal fluctuations of the head in the Lloyd sand range up to 44 per cent of the fluctuations in the level of the overlying tide-water.

Rate of transmission of artesian pressure--A word might be said here in regard to the rate of transmission of artesian pressure. As pointed out by Muskat [8, p. 669], the "velocity of propagation of disturbances within a fluid medium" is "equal to the velocity of sound in the fluid" and "may, therefore, be considered as effectively instantaneous" (this because of the comparatively low velocity of the fluid particles themselves). What is generally referred to as the "rate of transmission of artesian pressure" is a value of velocity determined by measuring the time required for the effect of pumping, or some such disturbance, to become appreciable or perceptible at a given distance from the source of the disturbance. As a result, rates of transmission determined in this manner are dependent on the means employed to measure the effect

of the disturbance. The more accurate the method of measurements employed, the higher will be the apparent rate of transmission. This is evident from a consideration of equation (30). Assume that $h_1 = -c\,Ei(-u_1)$ is the limit of accuracy of the means employed to measure the effect of a given continuous disturbance of constant strength. (If the depth to water were measured periodically by means of a graduated tape, h_1 would probably be 0.01 foot; if an automatic water-stage recorder were employed, h_1 might be as small as 0.001 foot.) As the exponential integral, $Ei(-u)$, is a single-valued function of the argument, $-u = -(r^2S/4Kmt)$, there is thus defined a value of u equal to u_1, corresponding to the limiting value of drawdown, $h = h_1$. If $(r^2S/4Kmt) = u_1$, then $t = (r^2S/4Kmu_1)$. In other words, the time required for a given continuous disturbance to produce a perceptible effect, that is to say, of magnitude $h = h_1$ at a distance r from the source of the disturbance, is directly proportional to the square of the distance. The apparent average rate of transmission between the source and a point at a distance r from the source is, therefore,

$$(r/t) = (4Kmu_1/rS) \qquad (44)$$

The nature of the exponential integral is such that as the argument of the function increases beyond bound the numerical value of the function approaches zero. Therefore, the smaller the value of h_1, the greater will be the value of u_1, and the greater also will be the value of (r/t) as given by equation (44). From this it might erroneously be concluded that if the limit of accuracy, h_1, could in some way be made to approach zero, the apparent rate of transmission would become infinite. Indeed, such a conclusion logically follows the foregoing statement. However, it should be borne in mind that the above equations are based upon the assumption that the transmission of pressure- effects is instantaneous, whereas actually the velocity of propagation of pressure-disturbances in an artesian aquifer is equal to the velocity of sound in the aquifer. Thus, if the means of measuring changes of pressure in artesian aquifers were sufficiently refined, it should be found that the rate of transmission of such pressure-changes is equal to the velocity of sound.

Acknowledgment--The writer is greatly indebted to his colleagues in the Geological Survey for timely suggestions and criticism, and especially to C. V. Theis, as many of the ideas expressed herein have been taken from his personal communications to the writer.

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ARTIFICIAL DRAINAGE OF LAND: STREAM-LINE EXPERIMENTS THE ARTESIAN BASIN--II

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In the Transactions of 1939 of the American Geophysical Union [see 1 of "References" at end of paper] photographs of stream-lines, obtained in a sand tank-model, of the flow of water from an artesian basin into horizontal equally-spaced circular drains were shown. The experimental results there given agree in a qualitative way with the analytical theory of the problem as presented by Farr and Gardner [2] and by Muskat [3]. The purpose of this paper is to extend the theory and to make quantitative comparisons with the experimental results. Expressions for the equation of a stream-line, for the drain-flux, and for the drain-spacing will be obtained.

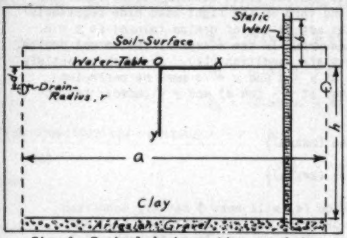


Fig. 1--Typical drain-section overlying an artesian basin

The analysis will follow that given by Muskat and is based on the following conditions and assumptions:

(1) The flow in the water-logged soil overlying the artesian basin is governed by Darcy's Law [4].

(2) The permeability of the saturated soil is constant.

(3) The water-table over the drain-lines is horizontal [5] and stands a distance h (see Fig. 1) above a horizontal layer of artesian gravel in which the pressure is constant and measured by the height b to which water in a static well bored into the artesian gravel will rise above the water-table.

(4) There are a large number of equally spaced, horizontal, circular drain-lines of radius r, distance a apart and lying at a depth d below the water-table.

(5) The pressure at the drains is atmospheric.

(6) The effect of the capillary fringe is negligible.

Assumption (4) implies that the flow-pattern between successive pairs of drains far removed from the end drain-sections repeats itself. Figure 1 represents such a typical drain-section. Conditions (1) and (2) imply that Laplace's equation

$$[(\partial^2\Phi/\partial x^2) + (\partial^2\Phi/\partial y^2)] = 0 \qquad (1)$$

is valid everywhere in the soil-water medium. In equation (1), Φ is the velocity potential function such that the velocity-components at P(x,y) in the medium are

$$v_x = -(\partial\Phi/\partial x) \qquad v_y = -(\partial\Phi/\partial y)$$

In gravity-flow problems such as the one under consideration the potential-function takes the form [6]

$$\Phi = K(p - \gamma g y) \qquad (2)$$

where

$$K = (k/\mu) \qquad (3)$$

and k = permeability of the soil, μ = viscosity of the water, p = pressure at a point P(x,y) in the medium, γ = density of the water, g = 980 in cgs units, x = horizontal coordinate, and y = vertical coordinate directed downward.

The boundary-conditions which the Φ-function must satisfy may be expressed analytically as follows:

(I) $p = p_0$ when $(d-r) \leq y \leq (d+r)$ and when both x and y are zero. (The pressure is atmospheric at the drains and at the water-table surface midway between the drains.)

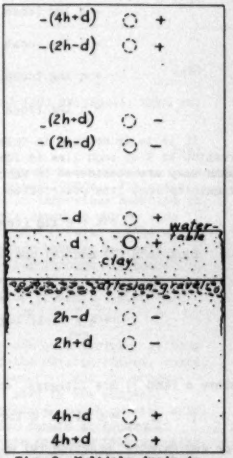


Fig. 2--Multiple drain images reflected alternately in water-table and gravel-soil interface [an aid in satisfying the boundary-conditions of La Place's equation]

(II) $(\partial\Phi/\partial y) = 0$ when $y = 0$. (At equilibrium no flow shall penetrate the x-axis.)
(III) $p = \gamma g(h+b)$ when $y = h$. (The pressure is constant at the artesian gravel-soil surface.)

The potential-function--The expression

$$\Phi = c + q \log \left\{\cosh [2\pi(y-d)/a] + \cos (2\pi x/a)\right\} + q \log \left\{\cosh [2\pi(y+d)/a] + \cos (2\pi x/a)\right\} \qquad (4)$$

in which c and q are constants will satisfy equation (1) and the above boundary-conditions, provided a, the drain-spacing, is not too large. The second term on the right-hand side represents the potential at a point P(x,y) in the medium due to the actual row of drains (sinks) at $y = d$. The third term represents the potential due to the image-array in the x-axis of the actual drains. This image-array is located at $y = -d$ and is used to satisfy condition (II). In order to satisfy condition (III) for large values of a, the drain-lines at $y = d$ and $y = -d$ must be reflected negatively in the line $y = h$. These rows will be located at $y = (2h-d)$ and $y = (2h+d)$; the potential arising from them will be

$$\begin{aligned} &-q \log \left\{\cosh [2\pi[y-(2h-d)]/a) + \cos (2\pi x/a)\right\} \\ &-q \log \left\{\cosh [2\pi[y-(2h+d)]/a) + \cos (2\pi x/a)\right\} \end{aligned} \qquad (5)$$

Addition of expression (5) to the right member of equation (4) will make Φ satisfy condition (III) accurately, but will violate condition (II). In order to satisfy conditions (II) and (III) simultaneously, it is apparent that multiple image-arrays arising from alternate reflections in the lines $y = 0$ and $y = h$ are needed. Figure 2 shows the position of a few such image-arrays. Making the substitutions

$$X = (2\pi x/a) \qquad Y = (2\pi y/a) \qquad D = (2\pi d/a) \qquad H = (2\pi h/a) \qquad (6)$$

the corresponding potential function is seen to be

$$\begin{aligned} \Phi = c &+ q \log [\cosh \overline{Y-D} + \cos X] + q \log [\cosh \overline{Y+D} + \cos X] \\ &- q \log [\cosh \overline{Y-(2H-D)} + \cos X] - q \log [\cosh \overline{Y-(2H+D)} + \cos X] \\ &- q \log [\cosh \overline{Y+(2H-D)} + \cos X] - q \log [\cosh \overline{Y+(2H+D)} + \cos X] \\ &+ q \log [\cosh \overline{Y-(4H-D)} + \cos X] + q \log [\cosh \overline{Y-(4H+D)} + \cos X] \\ &+ q \log [\cosh \overline{Y+(4H-D)} + \cos X] + q \log [\cosh \overline{Y+(4H+D)} + \cos X] \end{aligned} \qquad (7)$$

It is to be noticed in this last expression that when $y = 0$ the partial derivative with respect to Y of each line is identically zero; whereas if $y = h$, the value of the lines vanishes when they are considered in successive pairs beginning with the first two lines, and only the remaining last line contributes anything to Φ. Thus, when $y = h$

$$\Phi_{y=h} = c + q \log [\cosh \overline{Y+(4H-D)} + \cos X] + \log [\cosh \overline{Y+(4H+D)} + \cos X] \qquad (8)$$

Equations (7) and (8) can be generalized in the form

$$\begin{aligned} \Phi = c &+ q \log [\cosh \overline{Y-D} + \cos X] [\cosh \overline{Y+D} + \cos X] \\ &+ q \sum_{n=1}^{J} (-1)^n \log [\cosh \overline{Y-(2nH-D)} + \cos X] [\cosh \overline{Y-(2nH+D)} + \cos X] \\ &\qquad [\cosh \overline{Y+(2nH-D)} + \cos X] [\cosh \overline{Y+(2nH+D)} + \cos X] \end{aligned} \qquad (9)$$

where n (and J) are integers, and

$$\Phi_{y=h} = c + (-1)^J q \log [\cosh \overline{H+(2JH-D)} + \cos X] [\cosh \overline{H+(2JH+D)} + \cos X] \qquad (10)$$

For convenience, equation (9) may be written in the form

$$\Phi = c + q \varphi(X,Y) \qquad (11)$$

where

$$\varphi(X,Y) = \log [\cosh \overline{Y-D} + \cos X] [\cosh \overline{Y+D} + \cos X]$$
$$+\sum_{n=1}^{j} (-1)^n \log [\cosh \overline{Y-(2nH-D)} + \cos X] [\cosh \overline{Y-(2nH+D)} + \cos X]$$
$$[\cosh \overline{Y+(2nH-D)} + \cos X] [\cosh \overline{Y+(2nH+D)} + \cos X] \quad (12)$$

Using equations (2), (11), and the boundary-conditions, the constants c and q can now be evaluated. New symbols to be introduced are defined as follows:

$$\varphi_o = \text{value of } \varphi \text{ at } x = y = 0$$
$$\varphi_d = \text{value of } \varphi \text{ at } x = \pm a/2,\ y = (d \pm r) \quad (13)$$
$$\varphi_h = \text{value of } \varphi \text{ at } y = h$$

From condition (I)--putting $x = y = 0$

$$K(p_o - \gamma g d) = (c + q\varphi_d) \quad (14)$$

and

$$Kp_o = (c + q\varphi_o) \quad (15)$$

From condition (III)--putting $x = 0$, $y = h$

$$K(p_o + \gamma g b) = (c + q\varphi_h) \quad (16)$$

From equations (14), (15)

$$q = K\gamma g d/(\varphi_o - \varphi_d) \quad (17)$$

From equations (15), (16)

$$q = K\gamma g b/(\varphi_h - \varphi_o) \quad (18)$$

From equations (14), (16)

$$q = K\gamma g(b+d)/(\varphi_h - \varphi_d) \quad (19)$$

q will have a unique value if the right-hand members of (17), (18), and (19) are equal, that is, if

$$(d/b) = (\varphi_o - \varphi_d)/(\varphi_h - \varphi_o) \quad (20)$$

The value of q given by equation (19) has a conceivable physical significance. It is the value which is applicable if at a distance h above the artesian gravel an impervious membrane is placed having a row of drains distance d below it. The pressure at this membrane may be very much greater than atmospheric; then the second part of boundary-condition (I) will not be satisfied. If this fictitious membrane is such that it can be gradually raised through the soil without disturbing the soil-particles, yet preventing the passage of water through it, there will be a level reached where only atmospheric pressure is needed at the surface of the membrane midway between the drain-centers to keep it in equilibrium with the water-pressure. When this condition is reached equation (20) is valid.

If now the membrane is further raised to a new level, still below the soil-surface, lifting with it the air from the pore-space but not disturbing the position of the soil-particles, there will be a layer of air-free dry soil between the last position of the membrane and its present position--capillary action being disregarded. Supposing this layer of soil is now suddenly filled with water, the q of equation (19) subject to a time-varying boundary-condition will still be applicable. If the membrane is now removed, the water-table will not remain at this new level, but will gradually fall until it reaches the former position where equation (20) is valid. Equation (19) may be useful in computing the rate of fall of the artesian water-table which has been raised above its equilibrium-level by excess irrigation, rain, or other causes. So far attempts to compute this rate of fall have been unsuccessful.

Equation (20) gives the relation among the parameters r, d, b, h, and a when the water-table is at its equilibrium-level, and may thus be called the drain-spacing equation. This will be seen more clearly when the right-hand member of equation (20) is evaluated. The q's of equations

(17) and (18), unless equation (20) is true, have no significance, for equation (17) can be derived without a specification of the boundary-condition at y = h, and equation (18) can be obtained without specification of the boundary-condition at the drain.

The drain-flux--In order to show the physical significance of q, before evaluating the constants φ_o, φ_d, φ_h, etc., the flux into unit-length of drain will be computed. If the water-table is at its equilibrium-position, this flux is just equal to the quantity of water flowing upward per second through unit-width of the surface y = h lying between x = - (a/2) and x = (a/2) (Fig. 1). Expressed analytically

$$Q = \int_{-a/2}^{a/2} (\partial\Phi/\partial y)_{[y=h]}\, dx = 2\int_0^{\pi} (\partial\Phi/\partial Y)_{[Y=H]} dX \qquad (21)$$

where $(\partial\Phi/\partial y)$ is the upward velocity.

Now from equation (9)

$$\begin{aligned}\partial\Phi/\partial Y_{Y=H} = q\,[&\sinh \overline{H-D}/(\cosh \overline{H-D} + \cos X) + \sinh \overline{H+D}/(\cosh \overline{H+D} + \cos X)] \\ + q \sum_{n=1}^{j} (-1)^n\,[&\sinh \overline{H-(2nH-D)}/(\cosh \overline{H-(2nH-D)} + \cos X) \\ &+ \sinh \overline{H-(2nH+D)}/(\cosh \overline{H-(2nH+D)} + \cos X) \\ &+ \sinh \overline{H+(2nH-D)}/(\cosh \overline{H+(2nH-D)} + \cos X) \\ &+ \sinh \overline{H+(2nH+D)}/(\cosh \overline{H+(2nH+D)} + \cos X)] \end{aligned} \qquad (22)$$

and since $\int_0^{\pi} [\sinh A/(\cosh A + \cos X)]dX = \pi$, equations (21) and (22) lead to the result

$$Q = 2q(\pi + \pi - 4\pi + 4\pi - 4\pi + 4\pi \ldots) = 4\pi q \qquad (23)$$

if j is an even integer.

Thus $4\pi q$ is the quantity of water entering unit-length of drain per second. Numerical calculations using equations (17) and (20) as well as equations (29) and (32), (to be derived below), and taking K for clay [7] equal to 3.60×10^{-8} cgs units give the results that for h = 50 feet, a = 50 feet, d = 5 feet, r = 1/4 foot (so that when the water-table is at the equilibrium-position, b = 5.16 feet), Q = 7.25×10^{-3} cc per sec per cm of drain = 7.87×10^{-6} cubic feet per sec per foot of drain; and for h = 50 feet, a = 20 feet, d = 5 feet, r = 1/4 foot (so that when the water-table is at the equilibrium-position, b = 24.5 feet), Q = 11.2×10^{-3} cc per sec per cm of drain = 1.297×10^{-5} cubic feet per sec per foot of drain.

Computation of φ_o, φ_d, φ_h, etc.--Putting X = Y = 0 in equation (12) and reducing

$$\varphi_o = 2 \log [2 \cosh^2 (D/2)] + 4 \sum_{n=1}^{j} (-1)^n \log [2 \cosh (\overline{2nH-D}/2) \cdot \cosh (\overline{2nH+D}/2)] \qquad (24)$$

Putting X = π and Y = (D$\pm$R) in equation (12), where R is defined by R = $(2\pi r/a)$, and reducing it follows that

$$\varphi_d = 2 \log [2 \sinh (R/2) \cdot \sinh D] + 2 \sum_{n=1}^{j} (-1)^n \log (4 \sinh \overline{nH-D} \cdot \sinh \overline{nH+D} \cdot \sinh^2 nH) \qquad (25)$$

From equation (10), assuming j is sufficiently large and even

$$\varphi_h = \log [\cosh \overline{(2j+1)H-D} \cdot \cosh \overline{(2j+1)H+D}] \qquad (26)$$

Using the identities

$$\cosh \overline{A-B} \cosh \overline{A+B} = \cosh^2 A + \sinh^2 B \qquad \sinh \overline{A-B} \sinh \overline{A+B} = \sinh^2 A - \sinh^2 B \qquad (27)$$

equations (24) and (25) yield

$$(\varphi_o-\varphi_d) = 2 \log [\cosh^2 (D/2)/\sinh (R/2) \sinh D] + 2 \sum_{n=1}^{J} (-1)^n \log [\cosh^2 nH + \sinh^2 (D/2)]^2/[(\sinh^2 nH - \sinh^2 D) \sinh^2 nH]$$

$$= 2 \log [\coth (D/2)/2 \sinh (R/2)] + 2 \sum_{n=1}^{J} (-1)^n \log \frac{[\coth^2 nH + \sinh^2(D/2)/\sinh^2 nH]^2}{1 - (\sinh^2 D/\sinh^2 nH)} \qquad (28)$$

$$= 2 \log [\coth (D/2)/2 \sinh (R/2)] + 8 \sum_{n=1}^{J} (-1)^n \log \coth nH \quad \text{if } H>>D \qquad (29)$$

From equations (24) and (26) the denominator of equation (18) is

$$(\varphi_n-\varphi_o) = \log [\cosh \overline{(2J+1)H-D} \cosh \overline{(2J+1)H+D}] - 2 \log [2 \cosh^2 (D/2)] - 4 \sum_{n=1}^{J} (-1)^n \log \left\{2 \cosh [(2nH-D)/2] \cdot \cosh [(2nH+D)/2]\right\} \qquad (30)$$

an expression which is convergent for all values of J. In particular if J = 4, equation (30) can be written

$$(\varphi_n-\varphi_o) = \log [\cosh^2 9H + \sinh^2 D] - 2 \log [2 \cosh^2 (D/2)] + 4 \log \frac{[\cosh^2 H + \sinh^2(D/2)]\ [\cosh^2 3H + \sinh^2(D/2)]}{[\cosh^2 2H + \sinh^2(D/2)][\cosh^2 4H + \sinh^2(D/2)]} \qquad (31)$$

from which it is seen that

$$(\varphi_n-\varphi_o) = 2 \left\{H - 2 \log [2 \cosh (D/2)]\right\} \text{ for } H > 1/2, \cosh^2 H >> \sinh^2 (D/2) \qquad (32)$$

The drain-spacing equation--Since R = $(2\pi r/a)$, D = $(2\pi d/a)$, H = $(2\pi h/a)$, use of equations (28) and (30) with (20) will give a relation among the parameters r, d, a, h, and b. Likewise, use of equations (29) and (32) with (20) will give an approximate relation among these variables. It is

$$\frac{d}{b} = \frac{2 \log \dfrac{\coth \frac{\pi d}{a}}{2 \sinh \frac{\pi r}{a}} + \sum_{n=1}^{J} (-1)^n \log \coth \frac{2\pi nh}{a}}{[2 \frac{2\pi h}{a} - 2 \log (2 \cosh \frac{\pi d}{a})]} .$$

or, using the approximation $\sinh \frac{\pi r}{a} = \frac{\pi r}{a}$, neglecting the summation terms, and solving for b, it is

$$b = 2d \left\{\pi h/a - \log [2 \cosh (\pi d/a)]\right\}/\log [\coth (\pi d/a)/(2\pi r/a)]$$

For a set of values 1/4 foot $\leq$ r $\leq$ 1 foot, 5 feet $\leq$ d $\leq$ 10 feet, a $\leq$ 300 feet, b $\geq$ 50 feet, the value of b computed with this last expression agrees to the nearest foot with the value of b given by the more accurate expression involving equations (28) and (30). Furthermore, if [(h-d)/a] is greater than about 1/2, it can be shown that this last equation is very approximately equivalent to the approximate drain-spacing equation given by Muskat [8].

The theoretical drain-spacing relation can be compared with experimental results presented [1]. Photographs 8, 9, and 10 of reference [1] show the stream-line flow corresponding to field-cases in which the artesian overburden is 50 feet and the drains are nine inches in diameter and nine feet below the soil-surface. While taking these photographs no effort was made to determine how much artesian pressure-head would be permissible before the underground water would break through the soil-surface. In photograph 8, the drain-spacing a is 41 feet and the artesian head is eight feet above the soil-surface. No water penetrates the surface. The theoretical drain-spacing equation shows that an artesian head b in excess of 13 feet will be required before the underground water will penetrate the soil-surface. Photograph 9 has a = 82 feet and an artesian head above the soil-surface of four feet. Again no water appears to penetrate the soil-surface. Here, according to the theory, the artesian head b must be more than 4.51 feet above the soil-surface before the underground water will penetrate the surface. Photograph 10 of reference [1] is reproduced here as Figure 3. Corresponding to Figure 3, a = 164 feet and the artesian head is only two feet above the soil-surface, yet the drainage is seen to be decidedly inadequate.

Fig. 3--Inadequately drained land; one-half section corresponding to a drain-spacing of 164 feet [artesian head is only two feet above soil-surface; analytical theory predicts that underground water will penetrate surface when artesian head is 0.97 foot above soil-surface]

much of the underground water penetrating the soil-surface in its flow-path to the drains. The theory shows that in this case the pressure-head may be only 0.97 foot if the stream-line flow is to stay under the soil-surface.

The stream-line equation--The equation of an equipotential surface is obtained by setting the left-hand side of equation (9) equal to a constant; $\Phi = \Phi(X,Y) = \text{constant}$, so that

$$\Delta\Phi = (\partial\Phi/\partial X)dX + (\partial\Phi/\partial Y)dY = 0$$

and the slope of the equipotential surface is thus

$$(dY/dX)_{\Phi=\text{constant}} = -(\partial\Phi/\partial Y)/(\partial\Phi/\partial X)$$

and the negative reciprocal of this,

$$(dY/dX)_{\text{stream-line}} = (\partial\Phi/\partial Y)/(\partial\Phi/\partial X) \qquad (33)$$

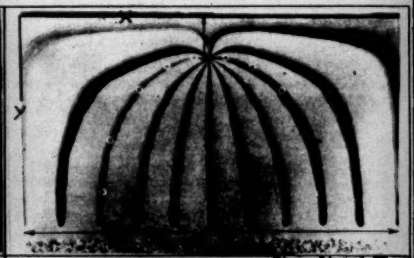
is the equation of a stream-line (stream-surface).

From the nature of the Φ-function (equation 9) it is evident that the integration of equation (33) will in general present extreme difficulties. If, however, the geometry of the problem is such that the first line of equation (9) will satisfy the boundary-conditions, the terms involving J become unnecessary, and equation (33) can be obtained in the relatively simple form

$$(dY/dX) = -(B \cos X \sinh Y + \sinh 2Y)/(B \sin X \cosh Y + \sin 2X) \qquad (34)$$

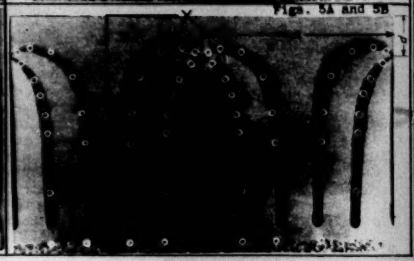
where $B = 2 \cosh D$.

Fig. 4A



Figs. 5A and 5B

Fig. 4B



Equation (34) can be put in integrable form by making the substitutions tan (X/2) = T, tanh (Y/2) = S, ST = U, (S/T) = V. The equation of separated variables thus obtained is $(B+2)[dU + (dU/U^2)] = -(B-2)[dV + (dV/V^2)]$, and this yields the integrated expression

$$B + C \sin X \sinh Y + 2 \cos X \cosh Y = 0 \tag{35}$$

or in explicit form,

$$Y = \log \left\{-B \pm [B^2 - A + (C^2 + 4) \sin^2 X]^{1/2}/(C \sin X + 2 \cos X)\right\} \tag{36}$$

where C is an arbitrary constant. This may be called the stream-line equation.

It is to be noticed that equation (36) does not involve the permeability of the medium. This is exhibited experimentally in Figures 4A and 4B, which are taken from last year's article [1]. These Figures are photographs of the sand-tank model stream-lines when the left half of the tank is filled with fine sand and the right half with coarse. There is no barrier separating the two sands and the boundary-conditions are the same for each half of the tank. The stream-line patterns are the same on each side of the tank, although the permeabilities are in the ratio of 1 to 4. The excess thickness of the lines on the left side is explained by the fact that the pressure at the inlets of the colored fluid on both sides of the tank-bottom was the same.

Equation (36) has been referred to as the stream-line equation. To be exact, it represents a family of stream-lines. The equation of one of the lines of this family which passes through P(X',Y') can be obtained by substituting the value of C [equation (35)], C = -(2 cos X' cosh Y' + B)/sin X' sinh Y', into equation (36). Figures 5A and 5B show photographs of experimentally obtained stream-lines [see reference 1] upon which have been plotted points (white circles) of the theoretical stream-lines.

Conclusion--The analytical theory as here presented agrees quantitatively with experiments performed in sand-tank models. The drain-spacing relation, when used in numerical application, shows that the drainage of water-logged artesian land by tile-drains will be prohibitively expensive in most cases, if it is to be effective. A feasible method to reclaim such land and at the same time develop irrigation-water is suggested by Farr and Gardner [9] and by Gardner and Israelsen [10]. These authors propose the use of vertical arrays of pump-wells, and have worked out the most economical arrangement for their installation.

The author wishes to thank his colleague in the Mathematics Department, Dr. M. T. Bird, for integrating equation (34), the stream-line differential equation.

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A CRITERION FOR INSTABILITY OF FLOW IN STEEP CHANNELS

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We say that the flow in an open channel is unstable if conditions are such that a disturbance of the free surface increases in magnitude as it moves downstream. A simple criterion for instability can be derived from Boussinesq's equation for the velocity of propagation of a volume-element of a wave, and a suitable formula for the variation of channel-resistance with depth. For mathematical simplicity we assume a wide rectangular channel and a wave-profile which is everywhere above the undisturbed surface. The notation is illustrated in Figure 1.

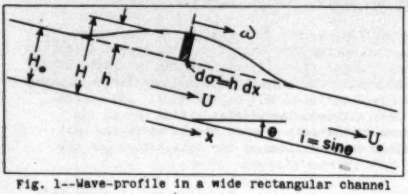

Fig. 1--Wave-profile in a wide rectangular channel

The direction of increase of the coordinate x is selected to coincide with the direction of U_0, the mean velocity of flow in an undisturbed cross-section. The deviation of the wave-profile from the original undisturbed surface is denoted by h, the undisturbed depth by H_0, and the total depth at any section by $H = (H_0 + h)$. Similarly, the deviation of the mean velocity in a cross-section under the wave from the undisturbed mean velocity is represented by u, so that the mean velocity at any section is $U = (U_0 + u)$.

We consider an element of volume, dσ. This element moves downstream with a velocity , which is called the velocity of propagation of a wave volume-element. Its height h is then a function of the time t, and we write

$$(dh/dt) = [(\partial h/\partial t) + \omega(\partial h/\partial x)] \tag{1}$$

Since $h > 0$, the criterion for instability is

$$(dh/dt) > 0 \tag{2}$$

which we wish to evaluate in terms of the channel-characteristics. The equation of continuity in terms of ω is

$$(\partial h/\partial t) + (\partial/\partial x)(h\omega) = 0 \tag{3}$$

Combining (1) and (3), we have

$$(dh/dt) = -\, h(\partial\omega/\partial x) \tag{4}$$

Using Boussinesq's method, the following formula for can be obtained

$$\omega = \omega_0 \left\{1 + [(2 + k_1)/4](h/H_0) + (k_2 H_0^2/6h)(\partial^2 h/\partial x^2) + 1/[2h\omega_0(\omega_0 - U_0)] \int_x^\infty [gHi - (\lambda/2)U^2]dx\right\} \tag{5}$$

where ω_0, the velocity of propagation of a wave of small height and curvature moving without change of shape, is given by

$$\omega_0 = U_0 + \sqrt{gH_0} \tag{6}$$

In equation (5) k_1 and k_2 are substitution-variables, $k_1 = 1 - (3U_0/\omega_0)$ and $k_2 = 1 - (U_0/\omega_0)$, and i is the slope of the channel.

The quantity λ is the channel-coefficient of friction, which in general is a function of the depth and is defined implicitly by the formula $\tau_0 = \lambda\,(\rho/2)\,U^2$, where τ_0 is the mean shear per unit area of wetted perimeter, and ρ is the density. Since in uniform flow the shear is balanced by the body-forces due to the surface slope, we have

$$gH_0 i - (\lambda_0/2)\,U_0^2 = 0 \tag{7}$$

λ_0 being the value of the coefficient when the depth of channel is H_0.

Equation (5) is applicable only when ω is nearly equal to ω_0. This is the case in the forward part and at the crest of a short wave. If we assume the wave-profile is symmetrical, then we have at the wave-crest, from equations (4), (5), and (6), $(dh/dt) = [gHi - (\lambda/2)U^2]/2\sqrt{gH_0}$, since $(\partial h/\partial x) = (\partial^3 h/\partial x^3) = 0$ at the crest.

The criterion given by (2) thus reduces to

$$gHi - (\lambda/2)\, U^2 > 0 \tag{8}$$

We now proceed to evaluate the above inequality in terms of the channel-characteristics. Recalling that $H = (H_0 + h)$ and $U = (U_0 + u)$, and writing $\lambda = \lambda_0 + (d\lambda/dH)h$, we have, using (7) and neglecting the small terms

$$gHi - (\lambda/2)\, U^2 = ghi - [(d\lambda/dH)/2]\, hU_0^2 - \lambda_0 U_0 u \tag{9}$$

The value of $(d\lambda/dH)$ depends upon the choice of flow-formulas. Adopting Manning's formula, $U = cR^{1/6}\sqrt{Rig}$, where R is the hydraulic radius, then since for a wide rectangular channel, $R = H$, we have from equation (7), $(U_0/\sqrt{H_0 ig}) = \sqrt{2/\lambda_0}$, and comparing the above two equations

$$\lambda = CH^{-1/3} \qquad (d\lambda/dH) = -(\lambda_0/3H) \tag{10}$$

In accordance with equation (10), equation (9) becomes

$$gHi - (\lambda/2)\, U^2 = (4/3)ghi - (2gH_0 iu/U_0) \tag{11}$$

λ_0 being eliminated with the assistance of equation (7).

The following expression for u can be derived from considerations of continuity: $u = [(\omega - U_0)/(H_0 + h)]h$, which is, approximately, $u = [(\omega_0 - U_0)/H_0]h$. Substituting this value of u in equation (11), there results $[gHi - (\lambda/2)\, U^2] = ghi\,[4/3 - 2(\omega_0 - U_0)/U_0]$, and since $h > 0$, the criterion (8) becomes

$$5U_0 > 3\omega_0 \tag{12}$$

In order to express this in terms of the slope, we transform the above, using equation (6), obtaining

$$U_0^2 > (9/4)\, gH_0 \tag{13}$$

From equation (7) we have $U_0^2 = (2gH_0 i/\lambda_0)$, and thus equation (13) becomes

$$i > (9/8)\, \lambda_0 \tag{14}$$

This is the criterion for instability of flow as based on Manning's formula. Jeffreys [see 1 of "References" at end of paper] and Thomas [2], using different methods, but both based upon Chezy's formula, obtain results which, when transformed to comparable form, are identical, namely

$$i > 2\, \lambda_0 \tag{15}$$

If the Chezy formula had been adopted in this analysis, equation (10) would have become $(d\lambda/dH) = 0$, hence equation (12) would have been $3U_0 > 2\omega_0$, and the final criterion would have been $i > 2\, \lambda_0$, in agreement with equation (15).

Jeffreys [3] admits some doubt as to the validity of his theory, since roll-waves are not observed until the slope is about 1 in 10.

These observations, however, give no definite information as to the magnitude of λ, and as long as such information is lacking, no definite conclusions as to the validity of either criterion can be drawn. This state of affairs clearly shows the need for more experimental data on the deformation of wave-profiles, which at the present time are all too few. In this particular case, the results might illuminate some interesting aspects of the relative merits of open-channel formulas.

References

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[2] Harold A. Thomas, Roll waves in steep channels, Trans. 7th Gen. Assembly Int. Assoc. Sci. Hydrology, Washington, 1939 (to be published).
[3] Vaughan Cornish, Ocean waves, Cambridge University Press, Cambridge, England, p. 154, 1934.

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GRAPHICAL INTEGRATION OF THE FLOOD-WAVE EQUATIONS

Harold A. Thomas

The partial differential equations expressing the fundamental law of unsteady flow in an open channel were stated about a century ago in the writings of Airy and other great masters of the classical hydrodynamics. However, reference to these equations in modern engineering literature is so infrequent as to justify a brief restatement of their underlying principles as an introduction to the present paper dealing with graphical methods for their integration. The notation to be used is shown in Figures 1 and 2. In the latter consider a lamina of length dx. The net unbalanced force acting on this lamina in the downstream direction is the difference

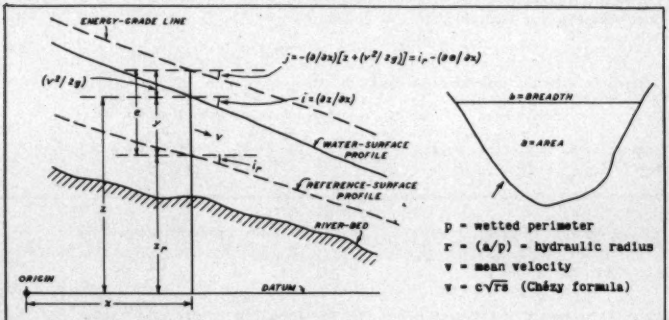
ENERGY-GRADE LINE
$j=-(\partial/\partial x)[z+(v^2/2g)]=i_r-(\partial e/\partial x)$
$(v^2/2g)$
$i=(\partial z/\partial x)$
WATER-SURFACE PROFILE
REFERENCE-SURFACE PROFILE
RIVER-BED
ORIGIN
DATUM
x
b=BREADTH
a=AREA
p = wetted perimeter
r = (a/p) = hydraulic radius
v = mean velocity
v = c√rs (Chézy formula)
y = stage, measured above reference-surface
q = av = discharge, q_r = kA = reference-discharge, where k is a constant
e = [y + (v^2/2g)] = specific energy
i = -(∂z/∂x) = instantaneous surface-gradient
j = [i_r - (∂e/∂x)] = instantaneous energy-gradient
α = -(1/g)(∂v/∂t) = localized acceleration-gradient
s = j + α = (v^2/c^2r) = true hydraulic gradient

FIG. 1—NOTATION

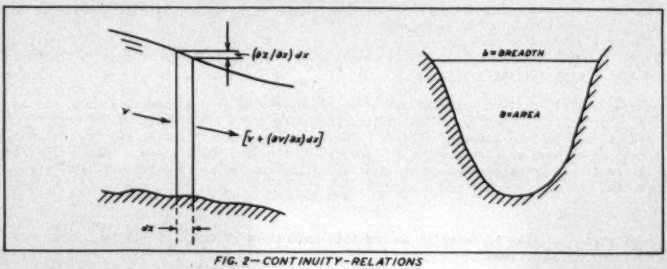

FIG. 2—CONTINUITY-RELATIONS

wa(- ∂z/∂x)dx of the total hydrostatic pressures on its upstream and downstream faces, minus the total frictional resistance (p dx)(v^2/c^2) on its contact surface, while the total acceleration of the lamina in the downstream direction is [(∂v/∂t) + v(∂v/∂x)]. Since the mass of the lamina is (w/g)a dx, we may therefore write

$$- wa(\partial z/\partial x)(dx) - (p\ dx)(v^2/c^2) = (w/g)\ a\ dx\ [(\partial v/\partial t) + v(\partial v/\partial x)]$$

or

$$(\partial z/\partial x) + (v/g)(\partial v/\partial x) + (1/g)(\partial v/\partial t) + (v^2/c^2r) = 0 \qquad (1)$$

This may also be written in the form

$$(\partial/\partial x)[z + (v^2/2g)] + (1/g)(\partial v/\partial t) + (v^2/c^2r) = 0 \qquad (1)$$

Moreover, in a short time-interval dt, the net inflow -[∂(av)/∂x](dx dt) into the lamina is equal to the area bdx of its upper surface times the rise (∂z/∂t)dt of this surface. That is,

$$- [\partial(av)/\partial x]dx\ dt = (bdx)(\partial z/\partial t)dt$$

or

$$[\partial(av)/\partial x] + b(\partial z/\partial t) = 0 \qquad (2)$$

Equation (1), based on the law of conservation of energy, and equation (2), based on the law of conservation of matter, are the fundamental partial differential equations defining the law of unsteady flow in an open channel. In this paper the following symbols and descriptive expressions are used to designate the various terms in equation (1). Some of these items are shown in Figure 1.

$i = -(\partial z/\partial x)$ = water-surface inclination or "instantaneous surface-gradient"
$j = -(\partial/\partial x)[z + (v^2/2g)]$ = energy-grade line inclination or "instantaneous energy gradient"
$\alpha = -(1/g)(\partial v/\partial t)$ = velocity-hydrograph inclination or "localized acceleration gradient"
$s = (v^2/c^2r)$ = "hydraulic gradient" or loss of energy per unit-weight per unit-distance traveled

In this notation equation (1) can be written in the form

$$s = j + \alpha$$

Equations (1) and (2) can be combined into a single equation by the introduction of a new variable φ such that $av = -(\partial\varphi/\partial t)$ and $a = (\partial\varphi/\partial x)$, φ being the volume of water between two cross-section planes which travel with the current.

While the integration of this equation by exact calculus methods under certain special conditions where some of the terms are assumed constant or zero affords intricate and interesting mathematical exercises, it is definitely not feasible to apply these exact methods to the solution of ordinary engineering problems of flood-routing in rivers. In the latter, a purely mathematical solution is precluded not only by the impossibility of handling the term involving v^2, but also by the complexity of the functional relationship between surface-elevation, cross-sectional area, hydraulic radius and roughness-factor, by the complexity of the boundary-conditions defined by the irregular contour of the channel-bed, and by the occurrence of tributary-inflows.

In the attempt to solve practical engineering problems dealing with flood-movements in rivers, various approximate methods for flood-routing have been devised. All these methods involve the replacement of the infinitesimal length- and time-intervals ∂x and ∂t in the fundamental equations by finite intervals Δx and Δt, the former usually representing distances between successive gaging-stations on the river, and the latter usually representing the time-interval (ordinarily 24 hours) between the taking of successive gage-readings. Typical methods assume that certain quantities, such as velocity, cross-sectional area, etc., pertaining to any given time or space-interval may be taken as equal to the corresponding quantities at one end of the interval, or else as the mean of the corresponding quantities at the two ends of the interval. Such assumptions, in combination with the coarseness of the time- and space-intervals used in typical flood-routing computations, are capable of introducing errors of serious and uncertain magnitude into the work. Errors are also introduced by the neglect of velocity-head and acceleration-effects. Errors which might be negligible in solving a single equation are capable

of accumulating to large size when the solution is repeated a great number of times as in a flood-routing computation. In general, it may be said that although the conventional flood-routing methods may give good results under some conditions, they have a tendency to be treacherous and unreliable. This is especially so in cases where the true hydraulic slope differs greatly from the water-surface slope as in rivers of flat gradient, where the rate of rise is very rapid as in rivers of steep gradient, and where the curvature of the flood-crest on the profiles and hydrographs is sharp in relation to the lengths of the time- and space-intervals, as in the great majority of cases met with in engineering practice. In all these cases it is difficult to make any reliable estimate of the probable magnitude of the cumulative errors which enter into the computation.

In this paper attention is called to the possibility of integrating the flood-wave equations graphically by a trial-and-error process involving the measurement of areas under curves, rather than the averaging of end-values. This method utilizes the full accuracy of the fundamental differential equations, and applies with equal correctness to the whole range of unsteady river-flow conditions from transient flood-peaks in a mountain torrent to tidal movements in an estuary. Where the stream-gaging and survey-data are quite complete, the accuracy of the graphical method may be made to approach closely to perfection. On the other hand, where the stream-gaging stations are far apart and the survey-information is fragmentary, the method permits a skilled person to make the best possible use of the meager data.

As a first example to illustrate the principles of the graphical method, it will be assumed that we are dealing with a river, indicated in Figure 3, on which there are several rated gaging-stations, and that a contour-map of the entire channel below high-water mark is available. During a given flood-period readings of stage at the gaging-stations are available at certain times--designated "Instant 1," "Instant 2," etc.--distributed through the period. It is also assumed that on tributary A a hydrograph of discharge is available at its mouth, and that it is proposed to construct a reservoir on this tributary, thereby producing a known change in its hydrograph. It is desired to determine how the stages on the main stream will be affected.

The accuracy and convenience of the graphical method--particularly where part of the data is non-continuous, as in the example under consideration--may be made a maximum by the choice of a coordinate system tending to produce smooth and undistorted curves. For this reason the river-stage y in this paper is referred not to the bed of the channel or to the zero of the gages, but to the water-surface corresponding to an arbitrary steady reference discharge q_r of medium magnitude, whose value at any station is some constant k (as for example, three cubic feet per second per square mile) times the drainage-area at that station. The notation pertaining to the reference-surface is shown in Figure 1.

At the start of the work certain preliminary curves, based on steady-flow conditions and the survey-data, must be prepared. The first is a reference-stage profile, as shown in Figure 4, giving values of z_r versus x. In those cases where no information is available on the channel-bed profile between gaging-stations, the reference-stage profile is sketched in as a smooth curve between the plotted points at gaging-stations, but in the present example where a contour-map of the channel-bed exists, the accuracy with which the reference-stage profile can be sketched is improved by plotting the profile of the "Thalweg" on the same sheet, as indicated in Figure 4. For each individual gaging-station the group of curves shown in Figures 5a, 5b, 5c, 5d, and 5e must be prepared, the last of these requiring the previous plotting of the curves shown in Figure 6.

Several methods may be used for expressing the valley-storage data between gaging-stations in the form of curves. A precise way of doing this, in case a contour-map of the river-channel is available, is the plotting of continuous profiles of cross-sectional area corresponding to various constant values of the stage y. However, due to backwater-storage in tributary valleys, these area-profiles tend to be jagged and irregular, and the accuracy of the work is not appreciably impaired if their irregularities are smoothed out. To accomplish the equivalent of this, the reach between each pair of gaging-stations can be divided into several sub-reaches--three of equal length being convenient in ordinary cases. For each sub-reach a curve of y_m versus a_m is plotted as indicated in Figure 7, a_m being the mean cross-sectional area (volume divided by length) and y_m the stage at the midpoint of the sub-reach, obtained by deducting from the water-surface elevation the value of z at the midpoint of the sub-reach as read from the reference-stage profile (Fig. 4). The principle governing the selection of the proper number of sub-reaches is that the storage-volume of any sub-reach corresponding to a given value of y_m must remain sensibly constant over the maximum range of surface-slopes encountered in the problem. An approximate preliminary computation will determine whether this requirement is satisfied, the error in question varying as the cube of the sub-reach length. The list of preliminary curves is completed by those represented in Figure 7.

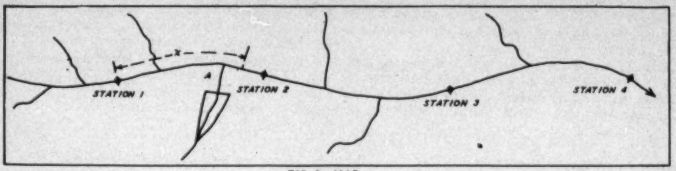

FIG. 3—MAP

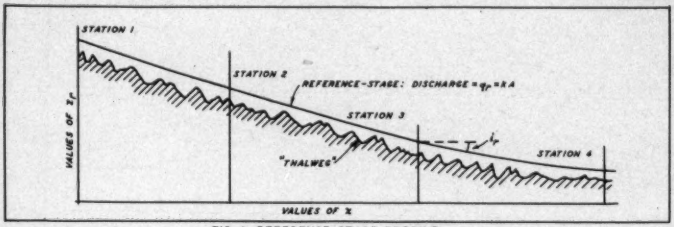

FIG. 4—REFERENCE-STAGE PROFILE

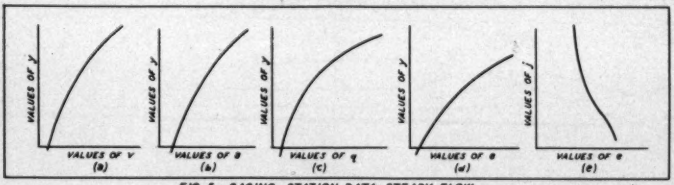

FIG. 5—GAGING-STATION DATA, STEADY FLOW

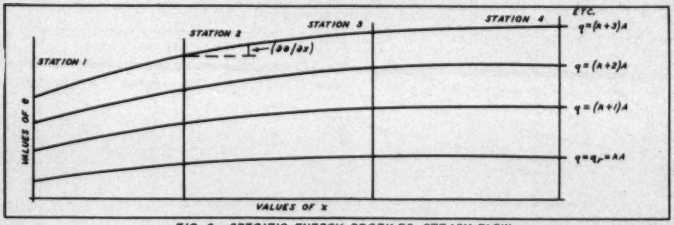

FIG. 6—SPECIFIC-ENERGY PROFILES, STEADY FLOW

FIG. 7—AREA-STAGE CURVE FOR SUB-REACH

In the present example, all local inflows into the various reaches between gaging-stations are regarded as unknown, except in the case of tributary A. Before solving the final problem values of these local inflows consistent with the river-gagings must be determined. This requires the conversion of the stage-readings into discharges by accurate methods consistent with the fundamental partial differential equation, that is, equation (1). The ordinary methods used for this conversion are insufficiently precise for the present purpose. The process is as follows: Plot the stage-profiles as shown in Figure 8. For each "station-instant" (as for example, at "a" or Section 3 at Instant 3) determine the approximate velocity v by Figure 5a and plot the result as in Figure 9, thereby obtaining hydrographs of approximate velocity from which $(\partial v/\partial t)$ can be measured and the "localized acceleration-gradient" $(1/g)(\partial v/\partial t)$ computed

for each station-instant. Also compute values of the velocity-head ($v^2/2g$) and the specific energy $e = [y + (v^2/2g)]$ for each station-instant, and plot-profiles of e versus x, as shown in Figure 10. From the latter values of $(\partial e/\partial x)$ can be measured, and values of the energy grade line slope j at each station-instant can be computed from the relation $j = [i_r - (\partial e/\partial x)]$. The true hydraulic slope s is then found for each station-instant by the relation $s = [j-(1/g)(\partial v/\partial t)]$, and the ratio of the corrected velocity v to the approximate velocity v_a is given by $(v/v_a) = \sqrt{s/s_n}$, the value of s_n being obtained from Figure 6, and the relationship $s_n = j_n = i_r - (\partial e/\partial x)$.

Using the corrected velocities, revise the curves of Figure 9, and repeat the process until

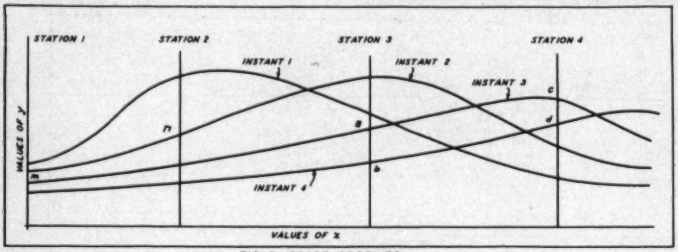

FIG. 8—STAGE-PROFILES

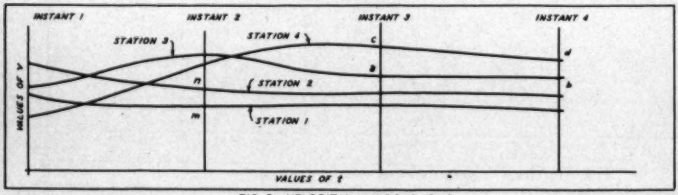

FIG. 9—VELOCITY-HYDROGRAPHS

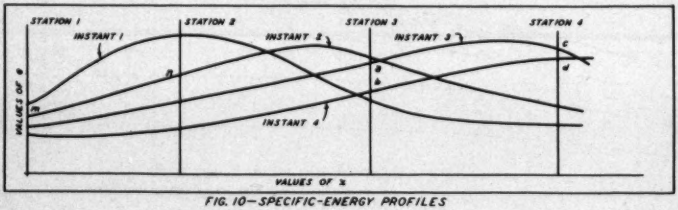

FIG. 10—SPECIFIC-ENERGY PROFILES

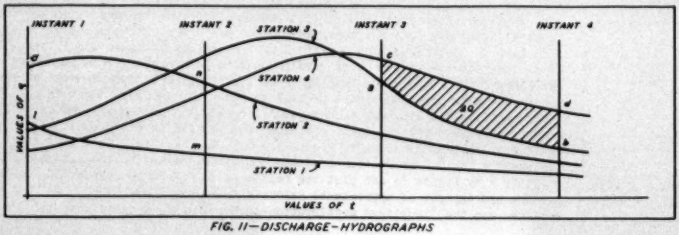

FIG. 11—DISCHARGE-HYDROGRAPHS

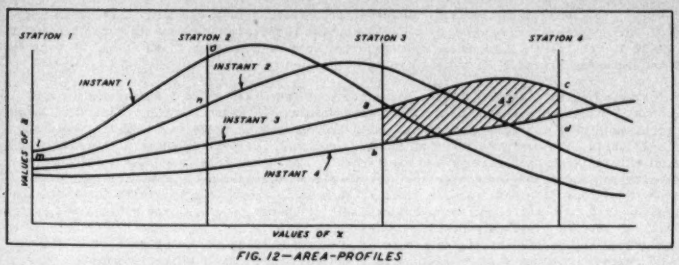

FIG. 12—AREA-PROFILES

the curves remain unchanged by further revision. With the aid of the corrected velocity-curves of Figure 9 and the area curves of Figure 5b, the true discharge-hydrographs are now plotted as in Figure 11. With the aid of Figure 7 and Figure 8, the area-profiles are also plotted as in Figure 12. On the latter the area of any "block" such as abcd, corresponding to a given reach and time-interval, represents the increase in storage-volume ΔS occurring in the reach during the interval, while on the hydrograph-sheet (Fig. 11) the area of the corresponding block, abcd, represents the excess ΔQ of the total outflow at the lower end of the reach over the total inflow at the upper end during the same interval. Therefore, the local inflow I entering the reach during the interval is given by $I = (\Delta S - \Delta Q)$. By this process the local inflows consistent with the river-gagings are computed for all the blocks.

FIG. 13—CURVES OF MEAN STAGE VERSUS MEAN BREADTH

FIG. 14—CURVES OF MEAN STAGE VERSUS MEAN AREA

We are now ready for the solution of the main problem, that of redrawing the profiles of Figure 8 to correspond to new values of the local inflow in Reach 1-2 due to known changes in the local inflow from tributary A, caused by operation of the proposed reservoir. The hydrograph of stage at Station 1 and the profile at Instant 1 are considered to be the same as before. The solution is a trial-and-error process, beginning with the determination of the new stage at Station 2 at Instant 2--indicated at m--in Figure 8, by extending a trial-profile mn downstream to this point from the known point n indicating the stage at Station 1 at Instant 2, and then going through the previously described process of establishing the corresponding lines on the hydrograph-sheet (Fig. 11) and the area-profile sheet (Fig. 12), and then determining a local inflow consistent with the trial-profile by measuring the difference between areas *lmno* on the two sheets. If this checks the known new local inflow, the location of the trial-profile is correct. If not, a new trial-profile is drawn and the work repeated, this being kept up until a check is obtained. The same process is extended to all the other blocks successively, thereby solving the given problem.

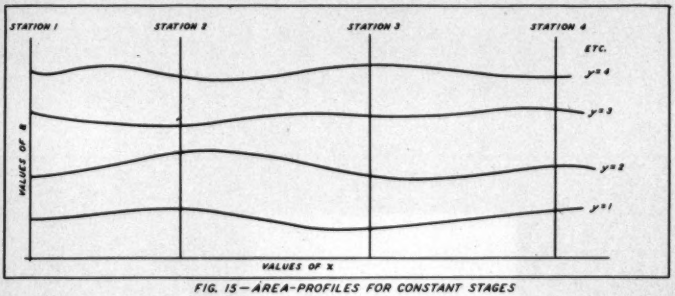

FIG. 15—AREA-PROFILES FOR CONSTANT STAGES

While it is obvious that this trial-and-error process is a laborious one, the economic importance of the problems to be solved by a flood-routing computation is usually more than sufficiently great to justify the time and effort required to obtain a solution which can be regarded as truly accurate and reliable.

The foregoing example assumed that a contour-map of the river-channel was available and that the local inflows between gaging-stations were unknown. However, in many practical flood-routing problems such a map is non-existent, while hydrographs of stage at the gaging-stations are available for a considerable number of floods, and local inflows are known at least approximately from rainfall-data and gagings on tributaries. Under the latter conditions the information requisite for the approximate plotting of the valley storage-curves (Fig. 12) may be obtained from the stream-flow data itself. This is done as follows: Starting with the known profiles of stage (Fig. 8), the corrected hydrographs of discharge (Fig. 11) are constructed by the trial-and-error process previously described. As already explained, the area of each "block" on these hydrographs represents the difference ΔQ of the total inflow and total outflow at the two ends of the reach during the given time-interval, and the increment of valley-storage ΔS occurring in the reach during the interval is found by the relation $\Delta S = (\Delta Q + I)$, where I is the known local inflow. Therefore, the approximate mean breadth b_m of the water-surface in the reach during the interval is $b_m = (\Delta S/\Delta y_m)$, where Δy_m is the change in stage at the middle of the reach during the interval.

The value of b_m thus computed will establish one point on a curve of b_m versus y_m as shown in Figure 13. By plotting many such points, based on the different blocks, for the various floods on record, the complete curve of b_m versus y_m may be built up. It is not to be expected that all the plotted points will fall exactly on a single curve, since three kinds of errors are present, namely, (1) errors in the rating curves at the gaging-stations on the river, (2) errors in the gagings and estimates of tributary inflows, and (3) errors due to neglecting the effect of slope and curvature of the water-surface profile when computing storage-volumes in terms of the stage at the midpoint of the reach. As soon as the shape of the curve of b_m versus y_m is determined approximately, an approximate correction for the third of the foregoing errors may be made on the basis of geometrical considerations, if so desired, or else the curve of b_m versus y_m may simply be drawn in a mean position among the plotted points. At extreme low water the curve will have to be extended arbitrarily to intersect the y-axis, as indicated by the dotted line in Figure 13. From the curves of b_m versus y_m, curves of a_m versus y_m are now constructed for the various reaches as indicated in Figure 14, using the principle $a_m = \int b_m dy_m$. By use of the latter curves, profiles of area corresponding to various constant values of y are plotted as indicated in Figure 15. On the latter profile-sheet the desired instantaneous area-profiles (Fig. 12) corresponding to any given instantaneous stage-profiles (Fig. 8) are readily plotted, thereby permitting the solution of any desired flood-routing problems. As previously explained, this solution consists in revising the trial-profiles until the areas of corresponding blocks in Figures 11 and 12 satisfy the law of continuity.

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A RATING-CURVE METHOD FOR DETERMINING SILT-DISCHARGE OF STREAMS

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(1) Introduction--During the course of investigations of the probable rate of silting which should take place in the proposed Denison Reservoir, an attempt was made to secure a correlation between suspended load of the Red River near Denison and the discharge. Observations of the silt-content had been made at intervals since 1930, both by the United States Department of Agriculture and the United States Engineer Offices. The United States Geological Survey has operated a stream-gaging station on the Red River continuously since October 9, 1923. Moreover, the United States Weather Bureau has maintained daily river-stages since 1906 and the daily discharge-record has been extended to provide a 33-year record. A correlation between silt-discharge in tons per second and water-discharge in cubic feet per second would permit a long-time record of silt-discharge to be established. By plotting the observations on logarithmic paper a straight-line relationship was found to exist between the two variables. The graph may be called a silt-rating curve. Such a rating curve for the Red River near Denison is shown on Figure 1. The method is presented with the hope that it may be found applicable to other streams. If such be the case, the utility of the scheme would be found in (a) the extension of the silt-record prior to the time of beginning observations and (b) the substitution of periodic silt-sampling for daily sampling. Either application involves the use of daily discharge-records. The silt-and-water-discharge relationship may also be a step toward the general solution of the problem of sediment-discharge of natural streams.

(2) Observational technique--The silt-sampling and analysis in the laboratory for the Red River near Denison, Texas, have followed, in general, the method described by Hemphill [R. G. Hemphill, Silting and life of southwestern reservoirs, Trans. Amer. Soc. Civ. Eng., v. 95, p. 1065, 1931]. Briefly, the samples are taken in an eight-ounce glass bottle at three points across the stream, namely, one-sixth, three-sixths, and five-sixths of the width. All samples are obtained at six-tenths of the depth. In the laboratory, the silt is separated by the use of filter-papers and dried at 110°C before weighing. Hemphill does not mention that the three-sixths-width observation is given a weight of two in averaging the observations. A more elaborate method was used by the United States Engineer Office during part of 1936. This involved 24 samples for one determination. Observations were made at eight verticals across the stream, with samples being taken at the bottom, middepth, and surface. The latter method was discontinued, as the additional accuracy did not appear to justify the labor required for streams of the size which were involved. All results in the laboratory were expressed in terms of dry weight of silt as a percentage of the weight of the original sample. The corresponding water-discharges in terms of second-feet were converted into units of tons per second. Finally, the products of the water-discharges and the percentages of silt by weight were calculated.

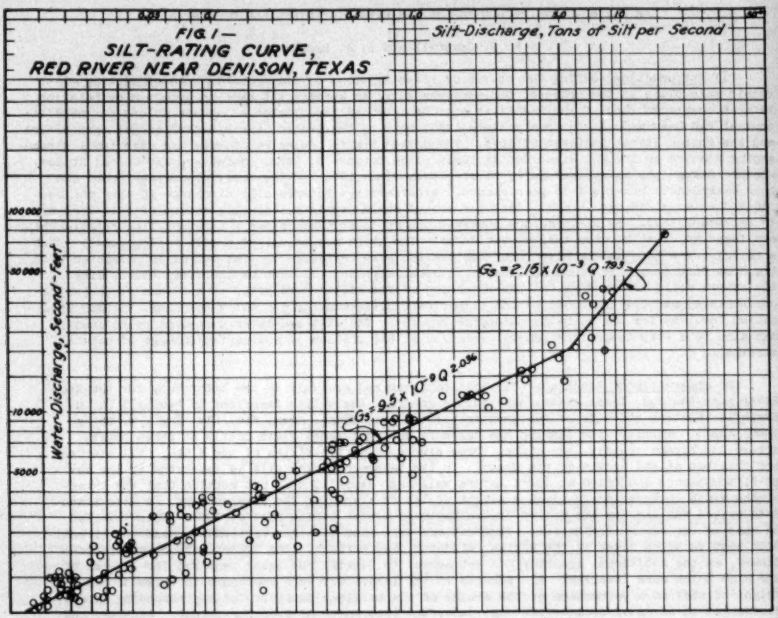
(3) Silt-rating curve--For the purpose of this paper, the average results of the three samples are connoted collectively as "observations." All observations above 1,000 second-feet made by the United States Engineer Offices on the Red River near Denison, Texas, have been plotted on Figure 1. Because of the great number of observations for flows less than 1,000 second-feet and of the wide graphical spread due to shifting beds, no rating curve has been constructed. For the analysis, an average of 0.005 ton per second was used for water-discharges less than 1,000 second-feet. It is seen that a linear relationship exists between the range from 1,000 second-feet to 20,000 second-feet although some spread of observations is obvious. This involves a range of stage of more than six feet. The general equation may be written

$$G_s = MQ^n \qquad (1)$$

where G_s is silt-discharge in tons per second, M is a coefficient involving density, Q is water-discharge in second-feet, and n is an exponent. Expressed definitely, equation (1) for the Red River near Denison has been found to be as follows

$$G_s = 9.5 \times 10^{-9}\ Q^{2.036} \text{ for } 1{,}000 < Q < 20{,}000 \qquad (2)$$

For discharges greater than 20,000 second-feet there is some evidence that the graphical slope of the relationship increases remarkably. Unfortunately, observations are rather sparse for the greater discharges. However, an equation is shown on Figure 1. Although positive proof is lacking, there is a strong indication in cross-sections from soundings that the stream ceases to scour so rapidly above 20,000 second-feet. At least, there is a sharp flexure in the stage-discharge relationship at this point. A tentative conclusion appears justified, namely, that the readily available material for suspended load is not being supplied in sufficient quantities to maintain the relationship which exists for lower discharges. Whether the linear relationship is definite at high flows, can not be determined until further flood-measurements are obtained.



(4) Physical features--It would serve to further clarify the aspects of the problem to describe the pertinent physiographic features of the Red River near Denison. There is an ample drainage-area of 38,291 square miles above the station. The confluence of the Washita River, draining the northern rim of the Basin, and the main stem of the Red River is only about six miles above the station. An outline-map of the water-shed has been given by Hathaway [Gail A. Hathaway, Estimating maximum flood-flow as a basis for the design of protective works, Trans. Amer. Geophys. Union, Part 2, p. 202, 1939]. The slope of the stream in the vicinity of the station is approximately 1.0 foot per mile. The width varies from 150 feet at low flows to 500 feet at high flows. The bed is a deep alluvium composed of material ranging from silt to medium sand. Extensive subsurface-investigations have been made in connection with the design of the Denison Project but a detailed description of these is beyond the scope of this paper.

(5) Verification of method--A valuable record of daily silt-determinations for the Red River has been made available by the Department of Agriculture, Bureau of Agricultural Engineering, Division of Irrigation. (This function has recently been transferred to the Soil Conservation Service.) The Department of Agriculture has taken daily samples at intervals to provide a total of five years or 60 months ending September 30, 1938 (recorded in Table 1). The sampling by the United States Engineer Offices at the same station were performed periodically as part of the stream-gaging routine. It is indeed fortunate that the two sets of observations are available for comparison. Table 1 shows a comparison of the total annual load by the daily sampling method and the rating-curve method. Although a few of the individual years show a considerable discrepancy between the methods, there is found a very close agreement of 1.5 per cent in the total of five years. The 14.8 per cent difference in 1933 may be due to a shift in the rating curve caused by a high flow on May 25. Likewise, there was a flood of 79,750 second-feet in September, 1936. The rating curve as shown on Figure 1 has been employed in this comparison and no attempt has been made to allow for shifts caused by natural adjustments of slope and cross-section at the station. It is significant that the two years of 1932 and 1938 with a very large total silt-load were in reasonably close agreement.

Table 1--Silt in Red River at Denison, Texas: Comparison of methods

Year	Period	Silt in tons		Difference	
		Daily sampling method	Rating-curve method		
				tons	per cent
1930	Sep.-Dec.	9,767,130	8,260,360	-1,506,770	-15.4
1931	Jan.-Dec.	9,883,020	10,439,460	+ 556,440	+ 5.6
1932	Jan.-Dec.	28,658,880	29,409,010	+ 750,130	+ 2.6
1933	Jan.-Aug.	14,834,270	17,028,760	+2,194,490	+14.8
1936	Oct.-Dec.	3,118,320	3,441,660	+ 323,340	+10.4
1937	Jan.-Dec.	15,465,060	11,617,000	-3,848,060	-25.0
1938	Jan.-Sep.	30,529,290	33,606,840	+3,077,550	+10.1
Total		112,255,970	113,803,090	+1,547,020	+ 1.5

(6) Application to other stations--The proximity of the exponent n to 2.0 in equation (2) suggests a parabolic relationship between silt- and water-discharge. Hence, the possibility was investigated for two stations upstream from the Red River near Denison. Silt-observations were available for the Red River near Gainsville, Texas, and the Washita River near Durwood, Oklahoma. The Gainsville station has physiographic features very similar to the Denison station, described above. The Washita at Durwood is a smaller stream with widths ranging from 80 feet at low water to 200 feet at bank-full stage. The control is a compact alluvium with clay predominating. The velocities are very low until a high stage is reached. The facts are presented in explanation of the curves shown on Figure 2. It should be noted that a very close agreement is found between the silt-rating curve for Gainsville and that for Denison. It was necessary to omit the individual observations from Figure 2 in order to allow a comparison between the three stations. It should suffice to state that the rating curves were originally constructed on logarithmic graphs upon which all observations were plotted. The portions of the curves exhibiting parabolic equations could not be made to fit the data better by shifting the slope from an indicated n of 2. The characteristics of the curves are listed in Table 2. An examination of Table 2 together with

Table 2--Characteristics of silt-rating curves

Station	Period applicable		M	N	Discharge-range applicable	
	From	To			Greater	Less
Denison	1930	1938	9.5×10^{-9}	2.036	1,000	20,000
Denison	1930	1938	2.15×10^{-3}	0.796	20,000	80,000
Gainsville	1936	1937	1.04×10^{-8}	2.0	100	40,000
Gainsville	1938	1939	3.85×10^{-8}	2.0	100	10,000
Durwood	1936	1937	4.5×10^{-16}	2.778	200	490
Durwood	1936	1937	9.2×10^{-8}	2.0	490	5,000
Durwood	1938	1939	1.35×10^{-15}	2.778	100	250
Durwood	1938	1939	2.7×10^{-7}	2.0	250	3,000

Figure 2 reveals interesting physical facts. The parabolic law applies throughout the entire observed range at Gainsville although a shift occurred in the rating curve after the high flows in February, 1938. This is expressed by the change in M from 1.04×10^{-8} to 3.85×10^{-8}. The parabolic law does not apply at Durwood for discharges below 590 second-feet on the older rating curve now below 250 second-feet on the more recent shift. The authors attribute this phenomenon to the fairly resistant clay-control which does not yield to scour until the velocity and depth reach appreciable magnitudes.

(7) Theory--For pragmatic reasons, the authors have elected to treat the theory briefly after the physical data have been presented. Within the range of applicability of the parabolic law, there exists a relationship between silt-discharge and conventional variables of open channel-flow. The equation for uniform flow in an open channel has been expressed conveniently by Boris A. Bakhmeteff [Hydraulics of open channels, McGraw-Hill Book Company, 1932, p. 13]

$$Q = K\sqrt{S_o} \qquad (3)$$

where K is the conveyance-factor and S_o is the normal slope. Substituting Q in equation (2) and placing n equal to 2

$$Q_s = MK^2 S_o \qquad (4)$$

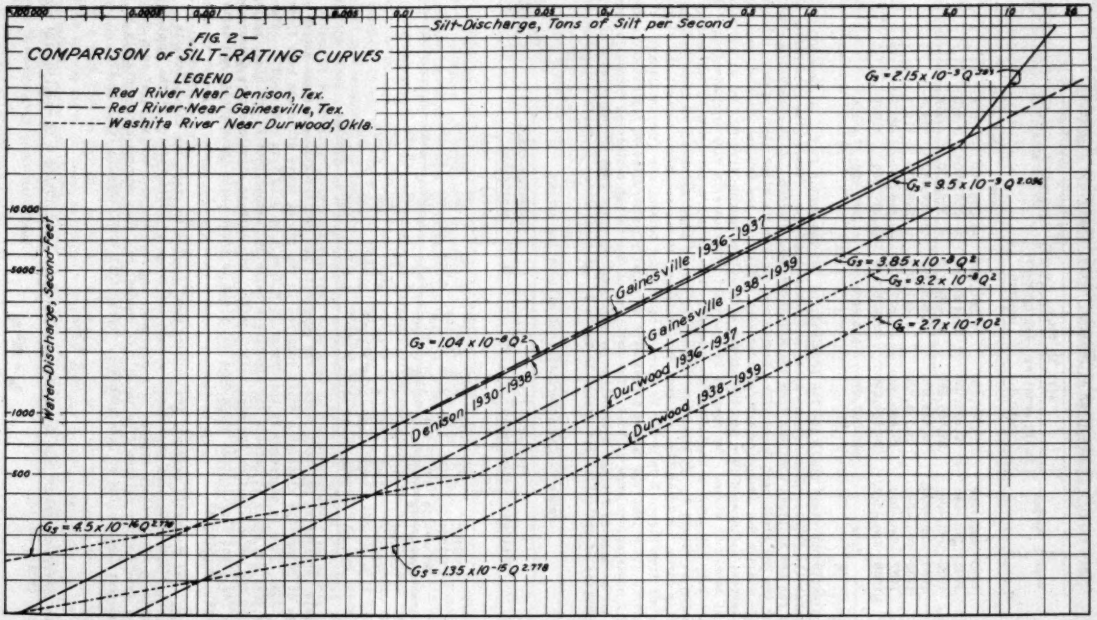


FIG. 2 —
COMPARISON of SILT-RATING CURVES
LEGEND
Red River Near Denison, Tex.
Red River Near Gainesville, Tex.
Washita River Near Durwood, Okla.
Silt-Discharge, Tons of Silt per Second
Water-Discharge, Second-Feet
10000
5000
1000
500
Gs = 2.15 x 10⁻³ Q 2.243
Gs = 9.5 x 10⁻³ Q 2.036
Gainesville 1936-1937
Gainesville 1938-1939
Gs = 3.85 x 10⁻⁸ Q²
Gs = 9.2 x 10⁻⁸ Q²
Gs = 2.7 x 10⁻⁷ Q²
Gs = 1.04 x 10⁻⁸ Q²
Denison 1930-1938
Durwood 1936-1937
Durwood 1938-1939
Gs = 4.5 x 10⁻¹⁶ Q 2.778
Gs = 1.35 x 10⁻¹⁵ Q 2.778

Solving for M, there follows

$$M = (G_s/K^2 S_o) \qquad (5)$$

Equation (5) serves only to demonstrate the nature of the coefficient M. It was observed in Table 2 that the value of M changes when there is a shift in the rating curve due to natural adjustments of slope and cross-section. Equation (4) indicates that the silt-discharge is a function of the normal slope as well as of the depth and cross-section, for the conveyance-factor is dependent upon each of the latter variables. The relationship of transporting power to slope and depth has long been recognized. It therefore appears that the parabolic law of the silt-rating curve produces a correlation with the known laws of open channel-flow which can be expressed as a simple equation.

(8) Conclusions--The foregoing study may be summarized briefly with a few conclusions as follows:

(a) Straight-line logarithmic relationships between silt-discharge and water-discharge were found for each station investigated.

(b) The silt-rating curve method has a distinct utility in extending records prior to the time of sampling, provided that shifts of the curve are not violent. The method is also of value in eliminating the cost of daily sampling. However, both of the applications should be used with caution until more data become available.

(c) With an ample supply of material for suspended load and a bed-material which scours easily, the silt-rating curve follows a parabolic law.

(d) The parabolic equation expressing the relationship between silt- and water-discharge can be correlated with natural laws of transportation of sediment which have heretofore been recognized.

(9) Acknowledgments--The greater portion of the data used was analyzed for purposes of hydraulic design for the Denison Reservoir, which is being constructed by the United States Engineer Department. The data from the Department of Agriculture were furnished by Dean W. Bloodgood of Austin, Texas. Most of the later silt-data were collected by his predecessors, Mr. Nickle and O. A. Faris. Free use was made of stream-flow data published by the United States Geological Survey. The information made available by all agencies is duly appreciated.

U. S. Engineer Office,
Denison, Texas

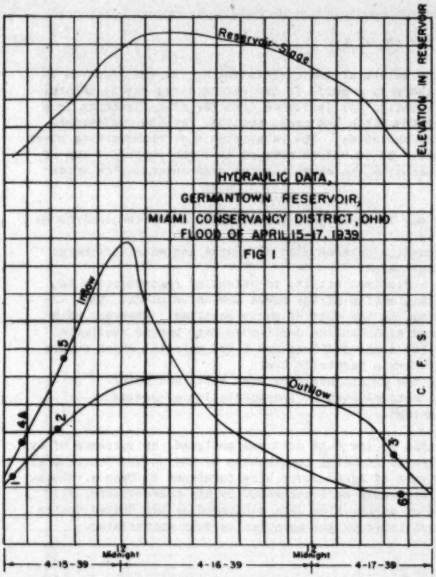
A STUDY OF SEDIMENTATION IN A MIAMI CONSERVANCY DISTRICT RESERVOIR

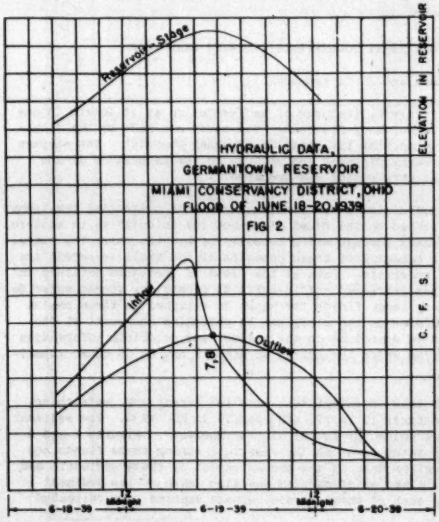
E. W. Lane and J. C. Kennedy

This report describes a study made of several features of sedimentation as it occurs in one of the flood-control basins of the Miami Conservancy District. The study was made by the Iowa Institute of Hydraulic Research in cooperation with the Miami Conservancy District. The samples were collected by the forces of the Conservancy District and shipped to the laboratory of the Iowa Institute where they were analyzed and this report was prepared.

The Miami Conservancy District reservoirs were built for the purpose of protecting the towns of the Miami Valley from floods and are located on the Miami River and its tributaries in western Ohio. The reservoirs are formed by earth-dams through which conduits or tunnels carry the normal flow of the river. When floods occur, the capacity of these conduits is too small to permit the water to pass as rapidly as it enters the reservoir. Part of the flood is therefore detained in the basins until the flow into the basin has decreased sufficiently to permit the stored water to escape through the conduits. Except in very large floods the water is retained in these basins at most only a few days. The principal purpose of the study was to determine what part of the sediment which is brought in by the floods is deposited in the basins, and to obtain information regarding the character of the sediment, from which the action of similar basins in other localities can be predicted.

Samples taken--The samples studied in this investigation, with two exceptions, were those carried by two small floods which occurred April 15 to 17, and June 18 to 20, 1939. The sediment carried by the stream was sampled above and below the outlet of the reservoir. Figures 1 and 2 show the variation of inflow, outflow, and water-level at the reservoir during these floods and the times of taking the samples. Table 1 gives data on the concentration of these sediments and the size composition is given in Table 2. A series of samples was also taken of the sediment deposited in various parts of the basin by each of these floods. These samples were collected



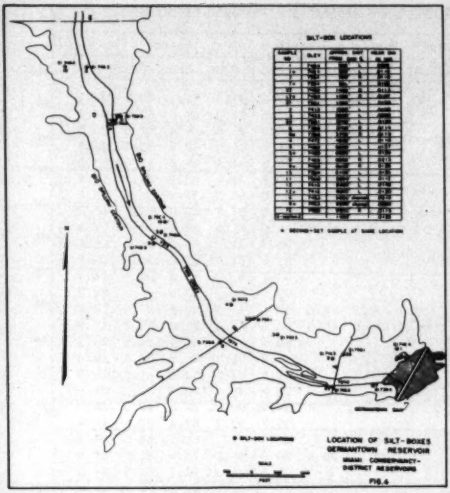


from silt-boxes (Figure 3) built for this purpose and placed at points distributed over the area of the reservoir as shown on Figure 4, which Figure also gives a table showing the elevation of the silt-boxes, their distance from the dam and the mean particle-size of the sediment deposited therein. Data on the size-composition of these samples are given in Table 3.

Deposited sediment--The composition of the material deposited in the Germantown Basin is shown on Figures 5 and 6. The heavy lines on Figure 5 represent the material deposited in the bottoms of the Germantown and Englewood reservoirs since they were constructed. If we consider clay to be particles less than 0.005 mm and silt those from 0.005 to 0.050 mm, these figures show that in the Germantown Reservoir the greater part of the deposit was composed of silt. In most of the silt-boxes less than 20 per cent of the sediment was clay and less than ten per cent was sand. Boxes No. 6 and 9 were near the creek-bed near the upper end of the area of deposit, where the currents were strong and therefore less fine material was deposited. Except in these two boxes, the deposits were of very similar composition, with a slight tendency to increase in coarseness with distance from the dam, probably due to the increase in current-velocity toward the upper end of the basin. The depth of the deposit varied with the height to which the water rose above the box at each point.

The deposit in the bottom of the Germantown Basin since construction was coarser than the deposits in the silt-boxes, probably because it was taken near the stream-bed where the current at times was strong enough to transport sand. The sample from the bottom of the Englewood Basin was

Fig. 3



considerably finer than that from a similar location in the Germantown Basin and somewhat finer even than the deposits in the silt-boxes of Germantown. In the Englewood Basin 40 per cent was clay and only six per cent was sand as compared with 18 per cent clay and 22 per cent sand in the Germantown. The greater amount of clay in the Englewood deposit is probably due to the longer period of detention of the floods in that Basin which gave time for more of the fine material to reach the bottom. The data on these reservoirs given in the Miami Conservancy District report [Miami Conservancy District Tech. Report, Part VII, pp. 209-210] indicate that the detention-period of the Germantown Dam in most floods probably was from two and one-half to four days, while in the Englewood Basin it was 5 to 12 days, that is, in two to three times as long, although the depth of flooding probably ranged from about 20 to 40 feet in both cases. The deposit in the bottom of the Englewood Basin contained very little sand, probably because the sample was taken further from the stream than the one at Germantown.

Table 1--Data on sediment inflow and outflow, Germantown Basin

Sample No.	Inflow or outflow	Date	Time	Total parts per million	Discharge
		1939	h m		sec-ft
1	Outflow	Apr. 15	10 00 a.m.	494	2400
4A	Inflow	Apr. 15	11 30 a.m.	1639	3650
2	Outflow	Apr. 15	4 00 p.m.	1459	4100
5	Inflow	Apr. 15	5 00 p.m.	1574	6850
3	Outflow	Apr. 17	10 00 a.m.	1658	3350
6	Inflow	Apr. 17	11 00 a.m.	342	1820
7	Outflow	June 19	2 00 p.m.	286	5550
8	Inflow	June 19	2 00 p.m.	266	5550

Table 2--Size-composition of inflowing and outflowing sediments, Germantown Reservoir

Sample No.	Per cent finer--Particle-diameters in millimeters													
	4.0	2.0	1.41	1.00	.84	.59	.42	.25	.149	.105	.074	.030	.0125	.005
1						100.0					95.4	84.9	67.4	53.3
2						100.0					98.6	93.5	79.8	60.5
3							100.0				98.7	88.7	70.5	45.6
4	100.0	96.4	89.8	78.5	72.2	58.0	47.0	42.4	41.5	40.8	40.1	33.4	26.2	15.7
4A									100.0	98.3	96.6	80.4	63.1	37.9
5						100.0					98.7	90.9	74.7	53.5
6							100.0				98.6	91.6	81.0	67.6
7							100.0				99.8	99.2	95.7	78.0
8							100.0				99.6	97.6	90.7	77.9

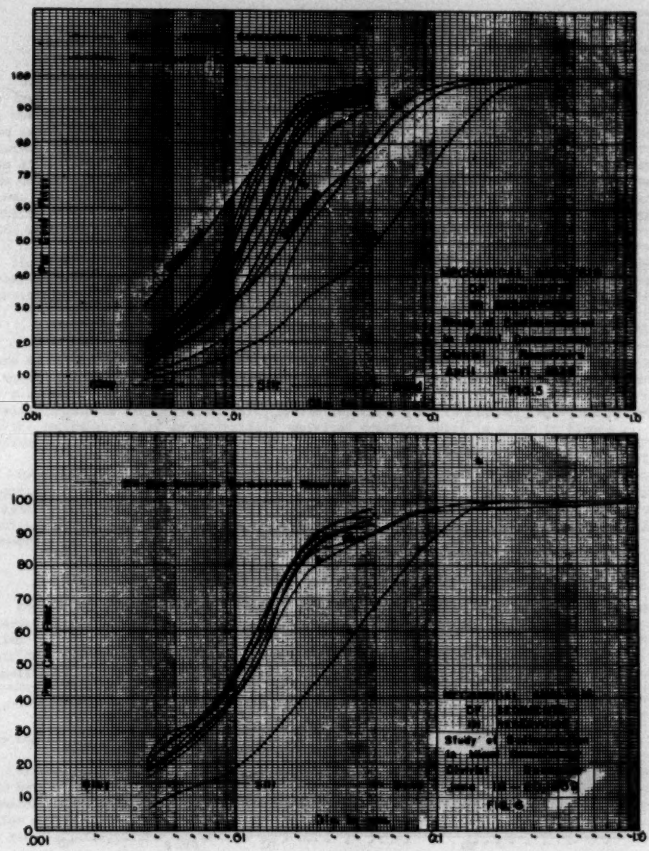
Table 8--Size-composition of deposited sediment, Germantown Reservoir

Silt-box No.	Per cent finer--Particle-diameters in millimeters										
	2.00	1.00	.42	.21	.149	.074	.050	.030	.020	.0125	.005
1							97.2	94.7	89.1	70.5	27.1
1*							93.0	90.0	83.0	57.0	26.0
2							98.2	95.6	89.4	63.5	25.3
3							97.0	94.0	89.3	66.0	26.0
4							96.5	91.9	80.8	57.0	23.5
5							90.6	83.1	65.1	39.5	17.4
5*							93.0	89.5	78.5	53.0	23.6
6			100.0	96.3	87.7	62.7	49.0	37.8	29.0	19.2	10.4
6*		100.0	99.8	99.3	97.5	81.8	68.0	51.0	38.0	24.0	11.0
7							93.3	90.0	80.0	56.7	25.5
7*							95.5	93.0	83.0	60.0	25.0
8							95.3	89.7	77.5	55.1	24.4
8*							97.5	93.0	83.0	61.0	28.7
9				100.0	99.8	93.0	82.0	63.0	46.8	27.5	13.0
9*			100.0	99.5	99.0	95.0	90.0	83.0	73.0	50.0	16.0
10							96.1	93.2	83.1	54.5	24.1
11							95.2	91.0	81.5	56.0	19.0
12							91.5	83.8	67.0	41.0	18.0
12*							94.2	89.5	80.2	51.0	24.0
15							94.9	90.0	75.0	49.0	20.0
20							95.7	93.3	82.4	53.5	19.9
22							92.9	89.1	80.1	54.5	25.5
22*	99.8	99.5	98.5	97.5	97.0	96.4	90.5	86.0	78.5	55.0	27.6
25							95.5	93.0	86.1	64.0	21.0
Mean	99.99	99.98	99.93	99.69	99.21	97.04	90.94	85.34	74.98	51.60	21.75
Germantown since construction			100.0	99.6	98.2	89.4	78.5	66.8	53.0	38.0	18.0
Englewood since construction							94.0	91.5	86.5	72.0	40.5

*Second set sample at same location in the later flood.

Suspended sediment--The size-composition of the suspended sediments in the incoming and outgoing water in these two floods is shown in Figures 7 and 8. From Table 1 it may be seen that large quantities of sediment passed out of the reservoir in the outflowing water, and therefore that the deposit in the Basin was considerably less than would have occurred had there been a long detention-period. That this reservoir fills very slowly is shown by the fact that the sediment deposited in the ten years following its construction amounted to only 0.4 per cent of the reservoir-capacity. Sample 4, as shown on Figure 7, contained considerable sand, which was too coarse to have been carried in suspension and was therefore probably bed-material picked up from the stream-bottom by the sampler. With this sand eliminated, the composition becomes 4A, which conforms generally to the other samples. Of the pairs of samples taken at approximately the same time, three pairs, namely, Nos. 1 and 4A, 2 and 5, and 7 and 8, showed finer material passing out of the reservoir than was entering it. In one pair, Nos. 3 and 6, the outflowing sediment was coarser, but in this case the flood was nearly over and the inflowing water carried very little sediment. These comparisons indicate, as might be expected, that a greater proportion of the coarse material was deposited than of the fine.

A comparison of the size-composition of the material deposited in the reservoirs with that sampled in the incoming and outgoing water, shows that the deposited sediment was much coarser than the suspended sediment-samples. The differences in size-composition of the inflowing and outflowing sediments was not great, which indicates that during the time not covered by samples, either the incoming water contained much more of the coarser sizes than was contained in the suspended samples or that there was a much greater difference in composition between the inflowing and outflowing water between sampling times than when it was sampled. Unfortunately, the data are not sufficiently complete to establish which was the case.



Conclusion--Although the data upon which this study was based are not sufficiently complete to warrant positive conclusions, they point very strongly to the conclusion that if the inflowing sediment is composed largely of silt- and clay-sizes, in retarding basins with short detention-periods like those at Germantown, a large part of the sediment, including most of the clay-sizes, will pass through the reservoir without deposit. If the detention-period is greater, as at Englewood, a greater proportion of the clay, and presumably also of the other sizes will be deposited. If a reservoir like that at Germantown is built with a recreation-lake formed by a low dam just above the flood-control dam, as is sometimes done, although there may be trouble from deposits in

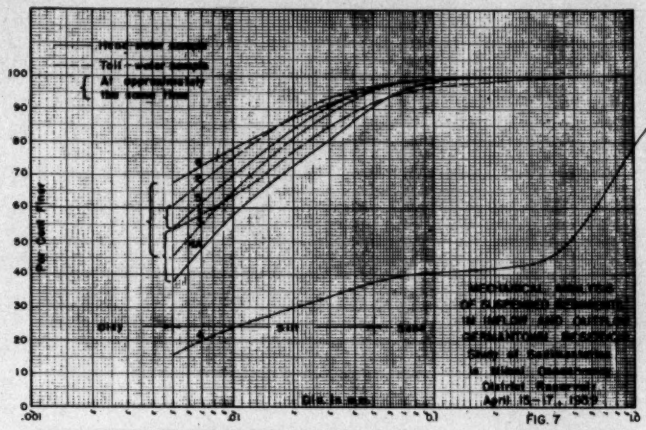


FIG. 7

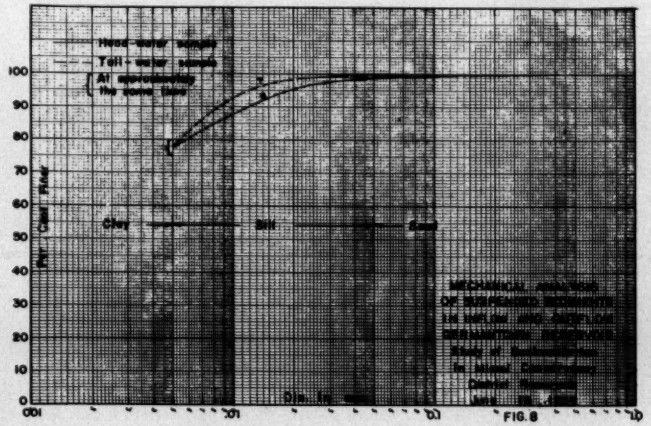


FIG. 8

the small reservoir, there is not likely to be trouble from deposits in the remainder of the reservoir. In general, it seems probable that unless the sediment-concentration in the inflow is unusually high, or the detention-period unusually long, sediment-deposits in retarding basins are unlikely to be a serious problem for many years.

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SUSPENDED-MATERIAL TRANSPORTATION UNDER NON-EQUILIBRIUM CONDITIONS

A. A. Kalinske

Our knowledge in regard to suspended-material transportation has been greatly increased in the last few years due to our more thorough understanding of the mechanics of turbulent flow. The vertical distribution of suspended material in rivers under equilibrium-conditions, that is, when there is no appreciable settling or scour, can be quite accurately predicted by the theory presented by O'Brien [see 1 of "References" at end of paper]. This theory permits the calculation of the total suspended material transported in a vertical section if the concentration at some one point, the velocity-distribution, and the hydraulic characteristics of the river are known. The correctness of this equation for vertical distribution of suspended material under equilibrium-conditions has been experimentally checked for artificial turbulence by Rouse [2]. Also, various data for natural rivers verify the theory quite well.

In order to relate the concentration of suspended material to the known hydraulic characteristics of a river and its bed-composition, Lane and the author in a paper [3] presented last year postulated the following fundamental relation

$$N_o/N_b = \varphi(c/\sqrt{\tau_o/\rho}) \qquad (1)$$

Where N_o is the concentration of suspended material having a velocity of fall c at the zero-level of suspension, N_b is the concentration of this material in the top layer of the bed-load, τ_o is the bottom-shear, ρ is the water-density, and φ means a "function of." Data obtained on natural streams and canals was presented which seemed to verify this functional relationship, and permitted the determination of an approximate empirical equation which is shown in Figure 1. In this plotting N_o is in parts per million and N_b is in per cent of bed-material for any given size.

Making use of this knowledge relating to transportation of suspended material for equilibrium-conditions, it is the purpose of this paper to analyze and study the non-equilibrium conditions. In general such conditions involve a decreasing or increasing of the suspended load, and from a practical standpoint this is a most important part of the whole general problem of sediment-transportation.

(A) Conditions causing increase or decrease in suspended load

According to the theory of diffusion in turbulent flow the rate per unit-area at which material of any size is transferred upwards by the turbulence is $\epsilon(dN/dy)$, where ϵ is the so-called "eddy-conductivity" or diffusion-coefficient and (dN/dy) is the slope of the sediment-distribution curve at a distance y above the bottom. Under equilibrium-conditions this rate of transference upwards must equal the rate of fall due to gravity, thus

$$cN = -\epsilon(dN/dy) \qquad (2)$$

(The negative sign is used since N decreases as y increases.)

If the above equality does not obtain then non-equilibrium conditions exist, and the difference between the right and left side of equation (2) indicates the rate at which there is a net transference, either up or down, of suspended material. The magnitude of this difference at the bottom would, of course, indicate the rate of settling of suspended material or the rate of placing material into suspension because of scour.

According to the theory on which equation (1) is based, under equilibrium-conditions for any value of the quantity $t = (c/\sqrt{\tau_o/\rho})$, a definite value of the ratio (N_o/N_b) must exist. For example, suppose a channel-bed is composed of material of a size characterized by velocity of fall c_1, then knowing the bottom-shear τ_o and the bottom-concentration N_b, we can determine the value of the bottom suspended-material concentration N_o from Figure 1. If the water entering this channel has suspended material so that the bottom-concentration is greater than N_o as determined from Figure 1, then settling will occur. Since the final equilibrium-concentration is known, the amount that will settle can be determined. However, the length of channel required for the settling to be completed is not known. Obviously a large amount of such settling cannot occur very long at any one point before the hydraulic characteristics of the channel are changed in some fashion. The speed with which important changes in the characteristics of the channel will occur depends, of course, on the rate of settling and the length of channel in which this settling occurs.

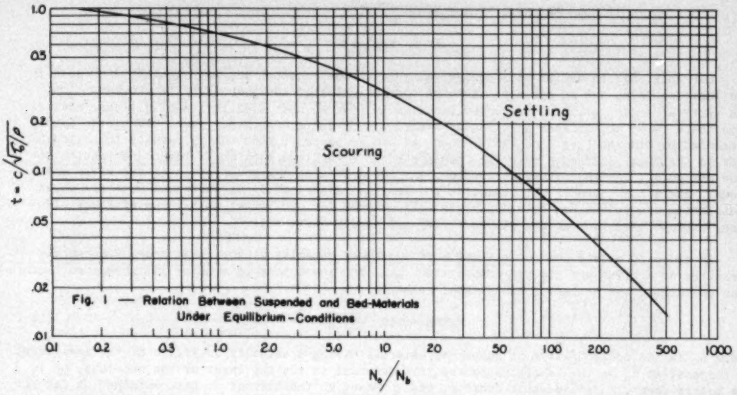


Fig. 1 — Relation Between Suspended and Bed-Materials Under Equilibrium-Conditions

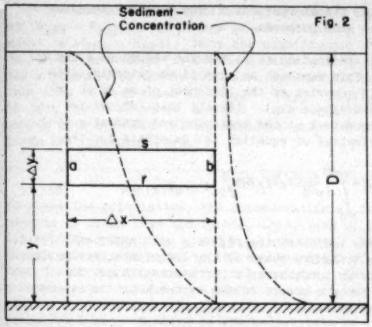
In the above example it was assumed that the bed-composition remained substantially constant in the settling reach of the channel. This, of course, only holds if we are dealing with material of practically uniform size. In most practical cases the material varies considerably in size, thus the bottom-composition along the settling reach changes, with the result that one of the "boundary-conditions" of our problem varies. This tends to complicate the solution of the problem considerably.

To further illustrate the fundamental ideas, let us take the problem where relatively clear water enters a channel having a bed composed of a material characterized by velocity of fall c. If the value of the bottom-shear is such that the quantity $t = c/\sqrt{\tau_0/\rho}$ is large enough, the bottom-material will be placed in suspension. Note that available data on suspended material seem to indicate that very little bottom-material will be placed in suspension if the value of t is about unity or greater. Of course, this does not mean that if for a given bottom-material t is unity or greater no scour will occur. It should be remembered that we are dealing only with the placing of material in suspension and not the transportation of material by bed-low movement or by any other process.

The time, or length of channel, required for equilibrium-conditions to be attained for the case where clear water enters a channel composed of a graded material is obviously quite complicated. Equilibrium-conditions for one size cannot be attained if conditions of equilibrium are not at the same time attained for the other sizes. Since, as long as the relative composition of the bottom-material changes, the value of N_b for any size changes N_b must also change. However, as analyses later will show, it appears that if everything else is the same the material having the greater velocity of fall will tend to attain equilibrium quicker.

If a canal or river is carrying a certain suspended load under equilibrium-conditions and the value of the mixing coefficient, ϵ, is decreased due to a change in the slope or depth, a certain amount of settling will occur. For the relatively very simple case of a uniform size of material the amount that will settle before equilibrium is again attained can readily be determined by the use of the curve in Figure 1. For a graded material the bottom will of course change from point to point due to the settling of the various sizes of material. Eventually equilibrium-conditions will be attained corresponding to the normal bottom-composition; thus the total amount that will settle could be estimated. Note from Figure 1 that for the larger values of t (or c, assuming the shear is the same), a change in the value of t due to a change in the shear will have a corresponding greater effect on the value of (N_o/N_b) than the same proportional change for the smaller values of t. This indicates that when the hydraulic conditions of a river change the effect on the coarser materials is relatively much greater than on the finer material.

Knowledge as to the time required for attainment of equilibrium-conditions is important for various engineering problems. For the very fine material equilibrium-conditions probably are never completely attained in our natural streams. That is why many times a considerable amount of fine material is carried along a river without a detectable amount of this fine material being



found on the bottom. However, for any settleable material, no matter how fine it is, the concentration increases towards the bottom; therefore, it is logical that, when equilibrium is established, the concentration of any size of material should be greatest at the bottom.

(B) Mathematical theory of non-equilibrium suspension

The general differential equation controlling the phenomena of suspended-material transportation under non-equilibrium conditions will be derived in an elementary fashion in order to make clear the physical processes involved. Consider, as shown in Figure 2, an element of water Δx units long, Δy units high, and of unit-width in the other direction. If we find the rate at which material passes through all four sides of this element, then the algebraic sum of all these rates is equal to the rate of change in concentration of sediment in the element with respect to time.

The net rate of transference of material per unit-area across the side r is $[\epsilon_y(dN/dy)_r - cN_r]$. The rate across the top side s is $[\epsilon_y(dN/dy)_s - cN_s]$. However, $(dN/dy)_s = [(dN/dy)_r - (d^2N/dy^2)\Delta y]$ and $N_s = [N_r - (dN/dy)\Delta y]$. Since the concentration varies in the x-direction there will be a net accumulation or subtraction of material from the elemental volume due to the mixing process of the turbulence in this direction. The rate of diffusion through the side a is then $[\epsilon_x(dN/dx)_a]$ and the rate of diffusion tnrough the side b is $[\epsilon_x(dN/dx)_b]$, where $(dN/dx)_b = [(dN/dx)_a + (d^2N/dx^2)\Delta x]$. The velocity of the water flowing through the element is U and since the concentration at a is different than at b, the net rate at which material is brought in or out of the element by the mean velocity of the flowing water is equal to $U(dN/dx)$ per unit-volume of fluid. The total rate of accumulation or subtraction can now be expressed and is equal to the rate of change of the concentration in the element with respect to time. As the element is reduced to infinitesimal size we obtain the following partial differential equation

$$(\partial N/\partial t) = \epsilon_y(\partial^2 N/\partial y^2) + \epsilon_x(\partial^2 N/\partial x^2) + c(\partial N/\partial y) - U(\partial N/\partial x) \qquad (3)$$

For equilibrium-conditions $(\partial N/\partial x)$ and $(\partial N/\partial t)$ are zero and the equation reduces to equation (2).

Even for the simplest of conditions the exact solution of the above differential equation is a most formidable mathematical problem. There are two simple cases for which the solution is quite identical; one is when the mean velocity U is zero and the other is when the concentration at any point does not change with time but the concentration does vary with distance downstream. The latter condition is of greater practical significance. The following simplifications and boundary-conditions will be assumed in order to obtain a mathematical solution: The value of ϵ_y does not vary with y, $(\partial^2 N/\partial x^2)$ is negligible in comparison to $(\partial^2 N/\partial y^2)$, the concentration when x is zero is zero, the concentration is zero at y = infinity (∞), and the concentration N_0 at y = 0, or the bottom, remains constant. The latter condition does not, of course, obtain even for a material of uniform size--in fact, N_0 itself varies with distance. However, valuable information may be obtained from the solution even with the above simplifications. The method for obtaining the solution will not be given since it would necessitate considerable space. The final result is

$$N = N_0 e^{-qy} - (2N_0/\pi)\int_0^\infty [n/(n^2 + q^2/4)]e^{(B\epsilon x/U)-(qy/2)}\sin nydn \qquad (4)$$

Where $q = (c/\epsilon)$, $B = -(n^2 + q^2/4)$, x = distance downstream, U = mean velocity in x-direction, and the value of the integral is obtained for all values of n from zero to infinity. When $x = \infty$ this equation reduces to

$$N = N_0 e^{-qy} \qquad (5)$$

This is the expression for sediment-distribution under equilibrium-conditions when ϵ is assumed a constant. Obviously the above equation is for conditions of scour since N was taken as zero when x = 0. A quite similar equation was obtained by Hayami [4]. (However, there appear to be

certain errors in his paper due to faulty mathematical transformations.) The integral in equation (4) can be evaluated by various methods available for such purposes.

The important item regarding equation (4) is its indication as to how the values of c and ϵ effect the time required for attaining equilibrium. This can best be seen if we determine from equation (4) the expression for the net rate at which scouring by the placement of material in suspension is occurring. This rate is of course $[\epsilon(dN/dy)_0 + cN_0]$. [Recall that (dN/dy) is negative.] Naturally the value of this quantity is greatest at the beginning and gradually approaches zero as time goes on. After taking the derivative of equation (4) we obtain for the rate of scour

$$\epsilon(dN/dy)_0 + cN_0 = -(2\epsilon N_0/\pi)e^{-(c^2x/4\epsilon U)} \int_0^\infty [n^2 e^{-(n^2\epsilon x/U)} / (n^2 + q^2/4)]dn \qquad (6)$$

The rate at which the above expression approaches zero indicates the rapidity with which equilibrium is obtained. An increase in ϵ, that is, in the diffusive power of the turbulence, obviously increases the rate of scour at any given point, while an increase in c, or sediment-size, decreases this rate, everything else being constant. Since c occurs in the exponent to the second power any changes in its value have a very pronounced effect.

If equation (6) is integrated from x = 0 to some distance x, we will have an expression for the total amount placed in suspension in the distance x. The expression for this amount is as follows

$$(UN_0\epsilon/c)\left\{1 - (2N_0c/\pi\epsilon)e^{-c^2x/4\epsilon U} \int_0^\infty [n^2 e^{-n^2\epsilon x/U} / (n^2 + q^2/4)^2]dn\right\} \qquad (7)$$

Note that when x is infinity, equation (6) becomes equal to $(UN_0\epsilon/c)$ which is the total amount carried in suspension per unit-time when equilibrium is obtained. If equation (5) giving the sediment-distribution for equilibrium-conditions is integrated from y = 0 to y = ∞, and multiplied by U, there is obtained $(UN_0\epsilon/c)$, which is as it should be, since if equation (6) gives the net rate at which sediment is placed in suspension then the total amount that will be carried in suspension eventually is the amount carried in suspension under equilibrium-conditions. The fact that we are dealing with an infinite depth instead of a finite one does not invalidate the general results but does simplify the mathematics. In the above analyses variation in velocity vertically was not taken into account in order that the problem may not be further complicated.

The value of ϵ varies from the top to the bottom of any channel. For the case of logarithmic velocity-distribution its value is

$$\epsilon = 0.40\sqrt{\tau_0/\rho}\,(1 - y/D)y \qquad (8)$$

In the above equations the value of ϵ was assumed constant but since this is not actually the case, probably the best that can be done is to use the average value of in the vertical cross-section. From equation (8) we find that $\epsilon_{ave} = (D\sqrt{\tau_0/\rho}\,/15)$. This indicates clearly how the average diffusive characteristics of the turbulence are effected by the depth, slope, and roughness of the channel.

(C) Approximate method of calculation

The complexity of the exact mathematical solution of the differential equation for non-equilibrium conditions of suspended-material transportation leads us to seek some other method of studying the variation in sediment-concentration. An approximate solution of a partial differential equation can be obtained by the use of finite increments in the calculations. The solution of the differential equation previously solved by rigorous mathematical means will be indicated. In finite increment-form this equation can be written

$$(\Delta N_y/\Delta x) = (\epsilon/U)(\Delta^2 N_x/\Delta y^2) + (c\Delta N_x/U\Delta y) \qquad (9)$$

The term ΔN_y is the change in concentration in the distance Δx at some constant height y from the bottom. The term ΔN_x is the change in concentration at any constant distance x with a change in position of Δy. The term $\Delta^2 N_x$ is the second difference or difference of two differences. Let the total height D be divided into finite increments, Δy, all of equal size. The distance x longitudinally will be divided into increments of length Δx. The increments Δy will be arbitrary while Δx will be related to Δy in the manner to be indicated. Let the subscripts i, j, and k indicate adjacent consecutive increments in the y- and x-directions.

The change in concentration with respect to x for constant height y, ΔN_y, can be represented as $(N_{yxk} - N_{yxj})$. The change in concentration with respect to y for constant distance x, ΔN_x, is equal to $(N_{xyk} - N_{xyj})$. Note the significance of the nomenclature; for instance, the term N_{xyj} is the concentration for constant value of x in the Δy-increment j and N_{xyi} is the concentration for x constant in the Δy-increment i, which is the increment just below the j-increment. The term $\Delta^2 N_x$ is then equal to $(N_{xyk} - 2N_{xyj} + N_{xyi})$. The j-increment is the middle, the k-increment is just beyond or above, and the i-increment is below or in back. Substitution of the above values into equation (9) and simplification of the resulting equation by letting $x = [U(\Delta y)^2/\epsilon]$, gives the following result

$$N_{yxk} = [(N_{xyk} + N_{xyi})/2] + [c\mathrm{U}(\Delta y)/2\epsilon](N_{xyk} - N_{xyj}) \qquad (10)$$

To start the calculation, the concentration at three adjacent increments in the y-direction is assumed or taken from the initial conditions of the problem. The value of x will be zero initially. Thus N_{xyi}, N_{xyj}, and N_{xyk} are known. The right side of equation (10) can now be calculated, and this is equal to the concentration of the middle increment at a distance $[U(\Delta y)^2/\epsilon]$ feet downstream from the original position. This calculation can be continued for other Δy-increments until a sufficient number of values are obtained for the concentration at the new distance downstream from the starting point. The process is then repeated at the point $x = [U(\Delta y)^2/\epsilon]$, etc. Setting up the calculation in convenient tabular form makes the work quite simple.

One of the advantages of this method is that it permits varying the value of ϵ with height without causing any great complication in the computations, and also the suspended concentration at the bottom need not be assumed to remain constant but can be changed in a manner to approximate its actual change. Equation (10) will not give this bottom-concentration; it must be assumed constant or its variation must be estimated. Of course, by the use of Figure 1, the value of N_o for any size of material can be predicted for equilibrium-conditions if the bottom-composition is known. Knowing the initial concentration of suspended material at the zero-level and the final value of the concentration at this level, the value of N_o at intermediate points can be estimated. A more exact calculation of the bottom suspended-material concentration, under non-equilibrium conditions, necessitates a more complete quantitative knowledge of the turbulence mechanism at the bottom than we possess at present.

(D) Summary and conclusions

Under equilibrium-conditions the suspended material carried by a stream is in some manner statistically related to the bottom-composition. Since true suspension is caused by turbulence, it is reasoned that the ratio of suspended material of any size at the zero suspension-level to the amount of this material on the bed, is a function of the velocity of fall and those hydraulic characteristics on which the magnitude of the turbulence depends. If this relation is known for equilibrium-conditions, then a useful tool is available for predicting whether, under any given conditions, a decrease or increase in suspended load will occur. Also the amount of the increase or decrease can be calculated.

The differential equation which controls the phenomena of suspended-material transportation under non-equilibrium conditions was developed. Its solution gives us an insight into the factors effecting the time required for changes in the suspended load to occur, particularly the time required for equilibrium-conditions to be attained. An approximate solution of the differential equation by the method of finite increments is also presented.

Further advances in our knowledge of the relation between suspended load, hydraulic characteristics of the stream, and the composition of the bed, depend to a large extent on a more thorough understanding of the mechanism of the turbulence at the bottom, that is, in the transitional zone between the bed-load and the zero suspension-level.

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DETERMINATION OF MANNING'S N FROM VERTICAL-VELOCITY CURVES

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(Published with the approval of the Director, U. S. Geological Survey)

Professor M. P. O'Brien [see 1, 2 of "References" at end of paper] has recently shown that data on the vertical distribution of velocity through the theory of turbulent flow as developed by Prandtl, Von Karman, and others may be applied to the determination of friction-coefficients in open channels. Hydrographers in making measurements of river-flow have often noticed that in streams having rough bottoms appreciable difference is generally found between the measured velocity at 0.2- and 0.8-depth. It is satisfying to note that Professor O'Brien's calculations are in accord with these general observations.

In an endeavor to study the subject and to develop the procedure further the methods suggested by Professor O'Brien have been applied to measurements of the flow of canals made by Fred C. Scobey [3] in 1913. Mr. Scobey's observations on each canal included measurements of a number of cross-sectional areas and surface-slope in selected reaches and measurements of flow by the vertical-velocity method, using the Price current-meter. The hydraulic elements of these reaches are published in Bulletin 194 of the Department of Agriculture. Mr. Scobey furnished the United States Geological Survey with the original notes which contain the results of current-meter observations at a number of positions in the vertical at 15 to 20 stations in each cross-section. As a rule these observations extended to within 0.2 of a foot of the bottom and were made at each even tenth-part of the depth. The material contained in Mr. Scobey's notes for a random group of suitable experiments were applied to formulas developed by Professor O'Brien for the evaluation of Manning's n. The following are the formulas used

$$n = 1.486\sqrt{k^2/g}\ (d^{1/6}/v_m)(v_2 - v_1)/[F(z_2/d) - F(z_1/d)] = 0.105(d^{1/6}/v_m)(\Delta v/\Delta F(z/d) \qquad (1)$$

$$F(z/d) = \left\{\log_e [1 - \sqrt{1 - (z/d)}]\right\} + \sqrt{1 - (z/d)} \qquad (2)$$

in which v is the velocity at distance z from the bottom; d is the depth; s is the energy-slope, v_m is the mean velocity in the vertical, and k is a universal constant having a value of 0.4.

Results of the calculations are listed in Table 1. The first two columns list the number of experiment, first as given in Bulletin 194 and then as given on the original notes. The third column gives the area of the discharge-measurement. The next four columns list the average hydraulic elements as given in Bulletin 194, and column (8) lists the values of n given by the Manning formula as given in Bulletin 652 [5]. The next column lists the value of n computed by the above formulas using the vertical-velocity curve given by Mr. Scobey. The computed values of n for each experiment in Table 1 are the average of the determinations at each vertical, and at each vertical are generally based on the quotient $[\Delta v/F(z/d)]$ applied between the lowest velocity-observation and the observation at 0.4-depth ($z/d = 0.6$). Although the quotients $[\Delta v/F(z/d)]$ were computed between each successive pair of velocity-observations within the bottom and 0.4-depth positions, these results were only noted for comparison and were not directly used in the computations. Great differences frequently existed between values of n computed for the several verticals in an experiment, which were presumed to exist as a result of natural differences in bottom-characteristics at the several locations. It should be noted that the basic observations, although carefully made by the usual stream-gaging procedure, have definite limitations as to accuracy and as to applicability to Professor O'Brien's equations. Each observation was made separately and represents the mean velocity at the indicated position in the vertical over a period of 30 to 60 seconds, but not a period concurrent with other observations in the same vertical. Since in many flowing streams the velocity at a given point appears to fluctuate in pulses above a mean, the measurements might produce values of v that are either not representative of the mean value or that are not representative of any existent simultaneous value. Moreover, many of the vertical-velocity curves displayed an excessive amount of inward bending at the surface. It is possible that the upper velocity-measurement may have been unduly affected by nearness of the meter to the surface. However, this effect is not believed to have appreciably affected these computations since the observations above 0.4-depth were not directly used, except insofar as they affected the mean velocity used in the formulas.

The values of n given in column (9) of Table 1 represent the computed values at the gaging sections whereas the values reported by Scobey are the average over a reach, and therefore the two are not necessarily entirely comparable. It should be noted, however, that in all experiments listed in Table 1, the reach included the gaging section and the reaches were all in artificial channels of sensibly uniform shape and composition. The computed values of n listed

Table 1--Summary of computations

Bull. 194 No.	Exp. No.	Area discharge measured	Mean area of reach	Mean hydr. radius	Discharge, sec-ft	Hydr. slope x 1000	Given n	Computed n	F(z/d) 0.6	F(z/d) 0.4	F(z/d) 0.2	F(z/d) 0.1	Revised n
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
12	24-S	59.16	60.60	2.54	221.20	0.2508	.0121	.0126	+.62	+.36	-.11	-0.83	0.0138
29	13-S	51.17	53.80	2.07	212.0	0.629	.0154	.0185	+.60	+.13	-.56	-1.06	0.0168
41	55-S	32.44	32.02	1.38	114.8	1.157	.0175	.0208	+.56	+.20	-.40	-1.18	0.0206
51	38-S	34.73	37.09	1.63	84.32	0.574	.0211	.0223	+.57	+.18	-.42	-1.14	0.0206
117	45-S	24.13	26.02	1.78	45.80	0.636	.0314	.036	+.63	+.36	-.68	-1.16	0.0304
120	1-S	139.76	139.81	2.62	310.84	0.17	.0167	.010	+.55	+.18	-.45	-0.71	0.0175
135	82-S	61.2	59.57	2.04	161.75	0.438	.0185	.0291	+.60	+.21	-.49	-1.47	0.0244
162	78-S	13.91	13.05	1.11	17.45	0.3795	.0233	.039	+.71	+.19	-.73	-1.20	0.0285
173	80-S	163.8	161.65	3.69	336.91	0.1682	.0221	.043	+.90	+.27	-.64	-1.23	0.032
195	1-H	96.7	93.00	3.02	218.3	0.38	.0261	.0310	+.56	+.13	-.53	-1.21	0.0292
199	56-S	28.97	35.24	1.27	35.01	0.263	.0285	.0257	+.50	+.15	-.58	---	0.0244
200	4-H	66.0	64.10	2.38	171.34	0.72	.0269	.0386	+.58	+.14	-.66	-1.36	0.0328
245	2-G	196.5	196.3	3.90	78.35	0.023	.0446	.025	+.18	0	-.40	-0.67	0.0498
255	43-S	27.4	25.70	1.81	40.93	0.603	.0342	.0265	+.39	+.24	-.20	-0.50	0.040
			Averages				.0242	.0270	+.57	+.20	-.49	-1.05	0.0272

in Table 1 have an average deviation of 28 per cent from the given values, although the average given value of n and the average computed value differ by only ten per cent.

After computing the value of n as described above, it was thought of interest to compare the vertical-velocity distribution defined by Scobey's measurements with that defined by equation (2). This comparison was made as follows. Since $F(z/d) = 0$ when $(z/d) = 1$ and v_2 = maximum velocity, O'Brien's equation may be rearranged [4] as follows

$$F(z/d) = - k[(v_{max} - v)/\sqrt{gds}] \qquad (3)$$

In determining n by O'Brien's method, the expression $\sqrt{s} = [v_m/(1.486/n)d^{2/3}]$ (Manning's equation) was substituted in the right-hand member of equation (3) and then solved for the unknown n. But in Scobey's experiments, the value of s (hydraulic slope) was determined on the basis of field-measurements and consequently all terms of the right-hand member of equation (3) are known from which $F(z/d)$ may be computed.

According to equation (3), the maximum velocity occurs at the surface. But in the measurements at hand, the apparent maximum velocity generally was found to be below the surface, and therefore the mean velocity was substituted for the maximum in equation (3). The mean velocity had the added advantage of being less in error than any single velocity-observation in a vertical. With this substitution the above equation becomes

$$F(z/d) = k[(v - v_m)/\sqrt{gds}] \qquad (4)$$

This equation was evaluated for each velocity-observation in each discharge-measurement referring to the mean velocity in the particular vertical. The computed values of $F(z/d)$ for equal values of (z/d) were averaged. These averages for each measurement are listed in Table 1. It will be noted that in each experiment, the mean velocity in the vertical occurred below a value of (z/d) of 0.4. With two possible exceptions, an appreciable amount of uniformity may be noted with respect to the computed values of $F(z/d)$. If these experiments had been made in perfectly uniform channels (that is, one in which all hydraulic factors are identical at each section) then use of the values of $F(z/d)$ given in Table 1 instead of those given by equation (2) would yield values of n identical with those given by Scobey. Experiments in Table 1 were made in channels that probably closely approached uniform character. As a test the computed values of $F(z/d)$ were applied to the determination of n with the results listed in the column headed "revised n" in Table 1. In nearly every experiment, the revised n was closer to the given n than that computed by the use of $F(z/d)$ given by equation (2). Average values of $F(z/d)$ for all experiments listed in Table 1 are given at the foot of the columns. Figure 1 shows the dimensionless graph of $F(z/d)$ in terms of (z/d). Graph A applies to equation (2) and graph B is a plot of the averages in

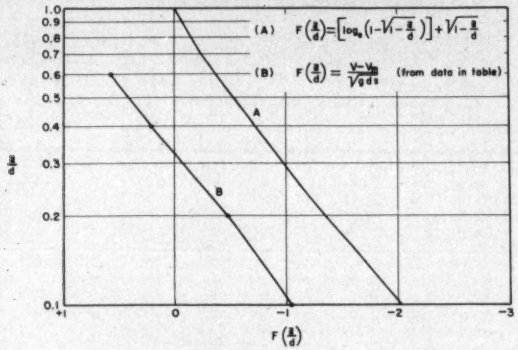

Figure 1.—Dimensionless plot of velocity-distribution in vertical

Table 1. The curves are very nearly parallel within the range shown. The displacement is due to the fact that equation (1) gives a value of F(z/d) of zero for (z/d) of one (at the surface) and the data in Table 1 are such that F(z/d) is zero at a point in the vertical whose velocity equals the mean [(z/d) = 0.33 by scale in Fig. 1]. In application to the evaluation of n by the procedure adopted herein, the displacement is of no significance, but since the slopes of these two lines are nearly the same, it appears that on the average equation (1) gives values which, although perhaps not perfectly suited to every channel-condition and in the absence of further information, may be considered to yield acceptable results, limited of course by other factors peculiar to this method of approach.

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CHANNEL-STORAGE AND UNIT-HYDROGRAPH STUDIES

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(Published with the approval of the Director, U. S. Geological Survey)

Recent studies of the rainfal-and-runoff relation tend towards treatment of the subject in two parts, namely, (1) the ground-phase, which includes the study of such processes as infiltration and evaporation, and (2) the channel-phase, which comprehends the study of the flow of water in the channel-system with particular reference to flood-wave movement. This paper discusses the channel-phase.

Flood-wave movement may be conceived to be subject to two principal kinds of operations, namely, uniformly progressive flow and reservoir-action. The first operation designates downstream movement of a flood-wave without change of shape which probably only occurs under ideal

conditions in a prismatic channel in which stage and discharge are uniquely defined at all places. Reservoir-action refers to transformation of a flood-wave that takes place as a result of reservoir-pondage. Flood-wave movement in natural channel systems (that are unaffected by debris-movements) is probably intermediate between the two ideal conditions cited--one or the other predominating in a particular place. However, the actual behavior is sometimes obscured because of the effects of tributary or other local inflow.

The process of determining progressively the timing and shape of a flood-wave at downstream points is called flood-routing. Several approximate methods of flood-routing have been described [see 1, 2, 3 of "References" at end of paper]. Thomas [1] sets up equations for the exact solution of flood-wave motion but as he indicates, practical difficulties make them virtually inapplicable to natural river-channels. Rutter and others [2] and McCarthy [3] describe methods which are convenient for general application to river-flood conditions and, if properly applied, can yield close results.

In brief, McCarthy has assumed that the volume of storage in a river-reach may be evaluated as follows

$$\text{Storage}_t = k[x I_t + (1 - x) D_t] \qquad (1)$$

Where I_t is inflow at time t and D_t is the discharge or outflow from the reach also at time t, and the factor k is the ratio between storage and discharge and has the dimension of time. The factor x, which is dimensionless, defines the manner in which the storage-volume is determined, relative to the inflow and outflow discharge-rates. The method assumes a uniform unbroken water-surface profile (uniform progression in discharge) between the upstream and downstream points on the reach, and assumes that stage and discharge are uniquely defined at these two places, and that k and x are sensibly constant throughout the range in stage experienced by the flood-wave.

In general it might be stated that the accuracy of a flood-routing storage-equation depends on the closeness with which the storage-volume can be approximated. As a first approximation it has been stated that the storage varies with the outflow discharge-rate as in a reservoir, and later McCarthy introduced the factor x to give expression to the so-called "wedge-storage" and therefore afforded a second approximation but which may be in error to the extent that the discharge in the reach does not vary uniformly from inlet to outlet. Rutter and others [2] similarly accounted for the "wedge-storage" but by graphical means, expressing storage based on river-profiles as a function of outflow-rate using the rate of inflow as a parameter.

The factor x in McCarthy's equation (1) is chosen such that the storage-volume is the same for a given weighted discharge, [xI + (1 - x)D], whether the river is rising or falling. The factor k is the slope of the storage-weighted discharge-relation, which in most flood-problems approaches a straight line. For spillway-discharge from a reservoir, x may be shown to be zero, since the reservoir-stage and hence the storage are uniquely defined by outflow-discharge, the rate of inflow being of negligible influence as an index of storage in the reservoir at any time. For uniformly progressive flow x = 0.50, and both inflow and outflow are of equal weight. In this wave, no change in shape occurs, the peak-discharge remaining unaffected. In reservoir-action the hydrograph is flattened. Analyses by the writer of many flood-waves has demonstrated that the time-interval between the center of mass of volume at the upstream point and at the downstream point is equal to the factor k. Figure 1 shows the effect of the value of x upon flood-waves.

The inflow-graph shown was arbitrarily chosen for illustrative purposes. The outflow-graphs were computed from the given inflow by the use of equation (1), using a value of k = unity, and the centers of mass of each of them regardless of the value of x is coincident, occurring one unit of time later than that of the given inflow-graph. Although coincident insofar as their centers of mass are concerned, the three outflow-graphs differ materially in shape--that for x = 0 (full storage-action) giving a flattened hydrograph, that for x = 0.50 being a reproduction of the inflow-hydrograph displaced by an interval equal to k, and that for x = 0.25 having intermediate characteristics.

Values of k are readily found either by computing the slope of the storage-discharge curve as described by McCarthy or by computing the center of mass-lag interval. However, the hydraulic conditions that determine the value of x that is applicable to a given reach are difficult to define. In most river-reaches the value of x is subject to variation when computed by McCarthy's method [3] depending on the relative amount of local unmeasured inflow. Local inflow is generally estimated, and the amount and the time-distribution of the estimated inflow correspondingly affect the computations of the flood-wave movement.

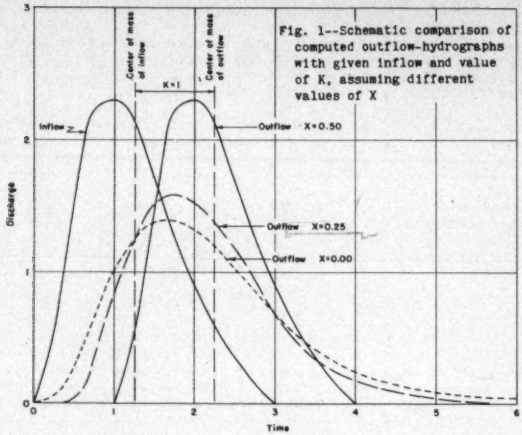

Fig. 1--Schematic comparison of computed outflow-hydrographs with given inflow and value of K, assuming different values of X

The value of x tends to approach zero in river-reaches that approach reservoir-conditions, that is, in those in which much of the river-profile is controlled by the discharge at a point downstream rather than by the discharge at the several points in the reach. At places within such reaches, the stage-discharge relations tend to become loops, with greater discharge on the rising side than on the falling side. The loop is produced either by variable slopes or by backwater from a downstream control. On the other hand, in prismoidal channels where stage and discharge are uniquely defined at all places, the value of x probably tends towards 0.50.

It is, of course, generally understood that in routing a flood through a river-system, it is necessary to break it up into reaches such that the river-surface can be safely assumed as uniform and unbroken. A series of pools and riffles or cataracts or excessively long reaches would not comply with this criterion, although special treatment in evaluating storage may remove some of the difficulties in using long channel-reaches.

An example of a uniformly progressive wave in a natural channel is shown in Figure 2. The wave was generated by the abrupt release of a volume of water at Guernsey Reservoir on the North Platte River. By the time it reached Bridgeport, Nebraska, 101 miles below, the wave had become stabilized as shown. The wave passed Lisco, Nebraska, 28 miles below Bridgeport with substantially the same shape. There was negligible inflow from tributaries, but there were small diversions for irrigation. The discharge at Lisco as shown in Figure 2 includes the estimated volume of such diversion between Bridgeport and Lisco. The lag-interval between their centers of mass is 17 hours. The peaks were 15 hours apart. Figure 3 shows the storage in the reach plotted against the discharge at Lisco, Nebraska, giving a loop showing a larger volume of storage for a given discharge during rising stages than during falling stages.

It should be noted that the river-surface between Bridgeport and Lisco was not uniform at all times. Thus at noon of June 2, the discharge at Bridgeport was 11,300 cfs, whereas downstream at Lisco the river had not yet begun to rise, the wave-front being somewhere between these two places. At this time the storage in the reach was 58,000 second-foot hours.

The abrupt change in discharge indicates that this reach would have been too long for direct application of McCarthy's methods. However, the discharges at intermediate points could be estimated from the hydrographs themselves, that is, the discharge half-way between is probably the average of that on the outflow-hydrograph 17/2 hours earlier with that on the inflow-hydrograph 17/2 following. The first gives 3,600 second-feet, and the second 3,200 second-feet. Consequently McCarthy's formula could be improved for some applications by using the average discharge during an interval instead of instantaneous discharges. The equation may be modified as follows

$$S_t = k\,[x\,I_{(t-2xk)} + (1 - x)\,D_{(t+2xk)}] \qquad (2)$$

where S_t is storage at time t, x and k are as before but $I_{(t-2xk)}$ is the average inflow during an interval 2xk preceding t and $D_{(t+2xk)}$ is the average discharge during an interval 2xk following t. When x = 0.50 the formula becomes $S_t = k[0.5\, I_{(t-k)} + 0.5\, D_{(t+k)}]$, and since $I_{(t-k)} = D_{(t+k)}$ then $S_t = kD_{(t+k)}$. When x = 0 equation (2) becomes $S_t = kD_t$. Therefore an approximation that is useful in some problems is suggested as follows

$$S_t = kD_{(t+2xk)} \qquad (3)$$

where x and k have the same significance and values as before.

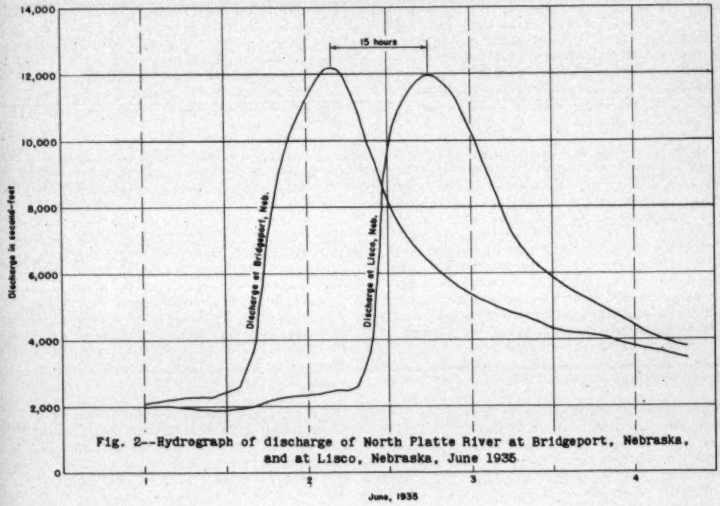

Fig. 2--Hydrograph of discharge of North Platte River at Bridgeport, Nebraska, and at Lisco, Nebraska, June 1935

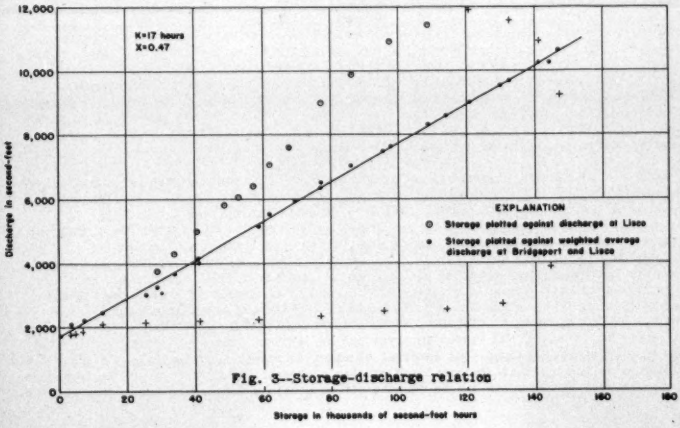

Fig. 3--Storage-discharge relation

Figure 3 also shows a well-defined relation between the volumes of storage and the weighted discharge as defined above by equation (2), using a value of x found by trial equal to 0.47, indicating nearly ideal uniformly progressive flow as might be confirmed by inspection of Figure 2. The relation closely approximates a straight line of slope equal to 17 hours and could have defined by equation (3) as well, using a time-interval of $2 \times 0.47 \times 17 = 16$ hours.

In comparing rainfall with the runoff from a drainage-basin, it is frequently of assistance to adjust the hydrograph of outflow from the basin for storage. Horton [4] and the writer [5] have described methods for doing this. The first-named reference made no allowance for accounting for greater storage on the rising side and the second only treated of the problem in which upstream gaging-stations were available. A method will be described for evaluating storage in the basin above the most upstream gage during a flood by the use of equation (3). The problem essentially is one of the selection of the proper values of k and x for the given basin, particularly the latter. Either equation (1) or equation (3) may be used. Although the use of equation (1) may be more accurate, its solution for the inflow requires more work than does equation (3). If equation (3) is used, improved results may frequently be obtained by evaluating $D_{(t+2xk)}$ as the geometric mean over the interval 2xk instead of using the arithmetic mean. When the range in discharge during the interval is small, the difference is not great.

In order to find a reasonable value of x applicable to entire basins, several basins were examined in which there were a number of small gaged upstream-areas. The storage in these basins at approximate intervals during two or three different flood-rises was computed by subtracting the total channel-inflow as indicated by the small gaging stations from the total outflow as given by the gaging station at the outlet.

Figure 4 shows a storage-loop computed by this method for Hoosic River near Eagle Bridge, New York (510 square miles), during the flood of September, 1938. The upstream stations in this problem were the following: Hoosic River at Adams, Massachusetts (46.3 square miles; North Branch Hoosic River at North Adams, Massachusetts (39.0 square miles); and Walloomsac River near North Bennington, Vermont (111 square miles). Figure 4 also shows the storage-loop closed by the use of equation (3) by plotting the storage at a given time against the mean discharge during an interval of eight hours following the given time. The points shown apply to the flood of March, 1936, as well as that of September, 1938. The slope of the average line shown is 19 hours and therefore $x = [8/(2 \times 19)] = 0.21$.

Comparison of the time-lag between center of mass of effective rainfall during the storm of September, 1938, and center of mass of direct runoff was computed as 21.5 hours. The difference of 2.5 hours may be accounted for in two ways: (a) The slope of the discharge-storage relation does not include the "inlet" time or initial lag-interval but includes only the time of transit in the defined stream-channels; (b) inadequacies of the selected method of evaluating total storage in Hoosic River Basin; analysis by use of the recession-curve as explained below gave a value of $k = 23$ hours.

Flood-waves in other basins that have been examined have indicated that as an average a value of $x = 0.25$ is approximately correct for evaluating the storage-effects and that the lag between rainfall and direct runoff is sensibly the same as the slope of the weighted discharge-storage curve. The value of $x = 0.25$ seems to indicate that on the average flood-flows in natural river-basins seem to be affected as much by reservoir-action as by uniformly progressive flow. There is flattening of the flood-crest due to reservoir-action and desynchronized timing of the flow from different parts of the basin, but not as much as would be indicated by the same volume of storage operated as a storage-reservoir.

The amount of storage in the river-channel system above a single gage can most readily be approximated by analysis of the recession-limb as suggested by Horton [4] and the writer [5]. In the problem of translating outflow into inflow it is desirable to know not only the total volume of storage but also its relation to the rising side as well as to the recession-limb of the hydrograph. For application to the rising side, as well as to the falling side of a hydrograph, cognizance must be taken of the x-factor, and according to the studies described above this factor for most basins may be taken as 0.25 and the recession discharge-storage relationship developed accordingly. Thus if equation (3) is used, such a diagram would show the relation between the discharge over an interval equal to 0.50 k (termed index-interval) and the storage at the beginning of that interval. Since k is not generally known, its value must first be approximated, before the 0.50 k index-interval can be derived. Table 1, following, indicates the method of computation employed. An interval of eight hours was used instead of exactly 0.50 k in this analysis on the basis of the preceding studies of Hoosic River Basin above Eagle Bridge, New York; the time-interval chosen can be rounded off to obtain a convenient tabulating interval.

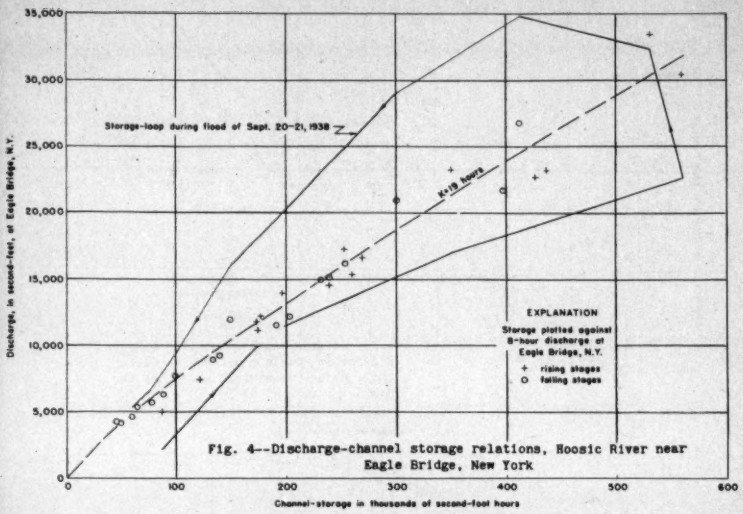

Fig. 4--Discharge-channel storage relations, Hoosic River near Eagle Bridge, New York

Table 1--Recession-curve analysis Hoosic River near Eagle Bridge, New York, flood of September 1938

Date	Time	Discharge, sec-ft	Base, sec-ft	Direct runoff, sec-ft	Storage, sec-ft 8-hr units	8-hr mean discharge, sec-ft
Sep. 22	8 a.m.	29,000	1,200	27,800	59,990	20,900
	4 p.m.	16,000	1,200	14,800	38,690	
	12 p.m.	9,500	1,200	8,300	27,140	
Sep. 23	8 a.m.	6,650	1,300	5,350	20,315	
	4 p.m.	5,260	1,300	3,960	15,660	
	12 p.m.	4,450	1,400	3,050	12,155	
Sep. 24	8 a.m.	3,900	1,400	2,500	9,380	
	4 p.m.	3,490	1,500	1,990	7,135	
	12 p.m.	3,150	1,500	1,650	5,315	
Sep. 25	8 a.m.	2,880	1,550	1,330	3,825	
	4 p.m.	2,630	1,600	1,030	2,645	
	12 p.m.	2,410	1,600	810	1,725	
Sep. 26	8 a.m.	2,270	1,650	620	1,010	
	4 p.m.	2,130	1,700	430	485	350
	12 p.m.	1,970	1,700	270		
					$\Delta S = 59,505$	$\Delta Q = 20,550$

$K = (\Delta S/\Delta Q) = (59,505/20,550) = 2.9$ eight-hour units = 23 hours

In adjusting a hydrograph for storage using equation (3), the storage at a given time is computed as k times the geometric mean discharge, $\sqrt[n]{q_1, q_2 \cdots q_n}$, over an interval equal to 0.50 k (or whatever value of x was used in computation of k as in Table 1) following the given time. Or a diagram may be prepared for the solution of equation (1) from known values of k and assuming x = 0.25 as shown in Figure 5, in which storage has been expressed in terms of the outflow-rate and the inflow-rate. The graphical method has an advantage of flexibility in that the

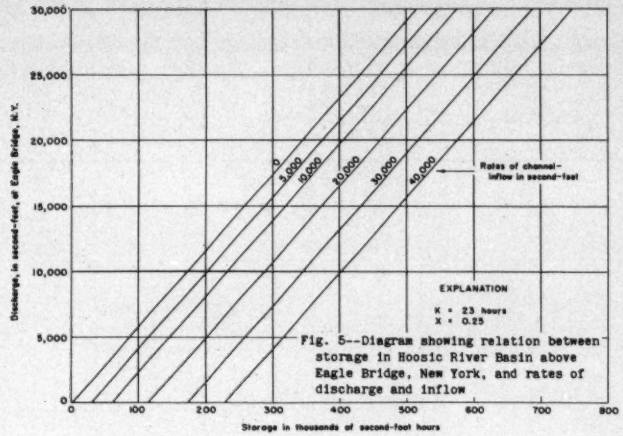

Fig. 5--Diagram showing relation between storage in Hoosic River Basin above Eagle Bridge, New York, and rates of discharge and inflow

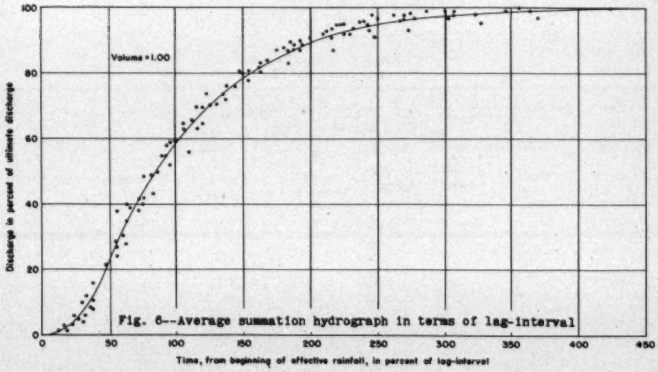

Fig. 6--Average summation hydrograph in terms of lag-interval

slope of the lines can be varied to allow for changes in k with discharge. In general the usefulness of equation (3) is limited to computing inflow from a graph of discharge.

After adjustment for storage by this method, the center of mass of the computed inflow will precede the center of mass of the observed direct runoff by an interval equal to k. If k equals the lag between effective rainfall and runoff, the adjusted hydrograph will compare favorably on a time-basis with the effective rainfall.

Hoyt [6] referred to the lag-interval as a possible means of correlating unit-hydrographs, and Snyder [7] has described methods of correlating the unit-hydrograph for a given basin with its lag-interval. Snyder has used the lag-interval between center of mass of effective rainfall and peak-discharge of the unit-hydrograph as the correlating factor. The writer suggests that the lag between center of mass of effective rainfall and center of mass of direct runoff is of greater flexibility, and moreover has other physical significances as described before. Moreover, determination of the lag-interval as thus defined is not limited to unit-storms. Its use as a measure of the channel-storage or unit-hydrograph characteristics of a basin seems to be promising.

The summation-hydrograph (S-hydrograph) is defined by Morgan and Hullinghorst [8] as the hydrograph of runoff from a basin with continuous generation of runoff. It affords a compact means for comparing the hydrograph-characteristics for storms of different duration. As described by Morgan and Hullinghorst, unit-hydrographs for storms of any effective length can readily be derived from the summation-hydrograph. This is done by placing two identical S-hydrographs along one another, displacing them by a time-interval equal to the length of the desired unit-hydrograph storm, and subtracting the ordinates of the one from the other at corresponding times.

Examination of a number of S-hydrographs for different basins suggests that lag-interval may be employed in comparing them. The results are shown in Figure 6. The ordinates of the summation-graphs have been expressed as a percentage of the ultimate discharge (volume of runoff divided by period of effective rainfall) and the abscissas as time from beginning of effective rainfall considered as a per cent of the lag-interval for the different graphs. The points shown apply to about ten different summation-graphs for areas ranging from 30 to 4,000 square miles in size in the Northeastern States.

When equilibrium is reached, that is, when the rate of outflow equals inflow, the volume of storage in the basin is equal to the area above the summation-hydrograph and below the 100 per cent discharge-line. Under these stabilized conditions, the ratio between volume and rate of discharge equals the lag-interval or in the case shown, unity.

The discharge of a unit-hydrograph based on the summation-hydrograph is

$$q = s[(\text{volume of runoff})/(\text{lag-interval})] \qquad (4)$$

where s is the slope of a chord of the summation-hydrograph (per cent of ultimate discharge divided by per cent of lag) over an interval equal to the duration of the period of effective rainfall. For a unit-hydrograph the volume of runoff is one inch and if the lag-time is expressed in hours, equation (4) becomes

$$s[646/(\text{log-interval})]$$

where q is rate in second-feet per square mile and s is dimensionless. The maximum slope of the summation-hydrograph, 1.20, occurs at 0.5 lag. This slope is the measure of the maximum discharge following an one-inch rainstorm of negligible duration (generally less than one-tenth lag). The corresponding discharge in second-feet per square mile is as follows

$$\text{Peak-discharge} = 1.20\ [646/(\text{lag-interval})] = [770/(\text{lag-interval})] \qquad (5)$$

Snyder [7] gives an average discharge of [400/(lag to peak)] for a storm of duration equal to the lag to the peak divided by 5.5. The two are not directly comparable.

The peak-discharge given by equation (5) or discharges defined by Figure 6 are averages defined by a number of hydrographs and may not fit any particular basin. No limits can be set for variations from the mean at this time. It is believed, however, that differences in shape of basin and arrangement of tributaries, slope of the several basins, and non-uniformity of rainfall would account for such variations.

The writer acknowledges the valuable assistance of L. C. Crawford of the United States Geological Survey in the preparation of this paper.

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A DISTINCTION BETWEEN BED-LOAD AND SUSPENDED LOAD IN NATURAL STREAMS

H. A. Einstein, Alvin G. Anderson, Joe W. Johnson

Introduction--Problems pertaining to the transportation of sediment by flowing water have been extensively studied by engineers and scientists during the last few years. Most of the various experiments have been concerned with either bed-load or suspended load, but seldom have they been studied simultaneously.

When bed-load and suspended load occur simultaneously in a flume or stream a distinct difference in their mechanical composition is often observed. A curve fitted to the plotted data from a mechanical analysis of the bed-material shows a distinct break. This break occurs most commonly in the data plotted from samples taken in mountain streams where the bed-material is extremely coarse. For instance, in the Rhine River, Switzerland [see 5 of "References" at end of paper] the bed-material ranges in size from pebbles 5 mm in diameter to boulders 100 mm in diameter and greater. Between boulders and in protected pools, however, sand one mm in diameter and finer is found, whereas particles ranging in size from one to five mm are not present. The explanation for this size-distribution has been that the material greater than five mm in diameter moves as bed-load and the material finer than one mm in diameter moves as suspended load. Particles ranging in size from one mm to five mm in diameter occur rarely for certain geologic or hydraulic reasons [3].

Observations indicate that the bed-load of streams is pushed, rolled, or saltated along the bed, while the suspended load is distributed throughout the whole cross-section. This difference in method of transportation has been made a criterion for the distinction between bed-load and suspended load; that is, bed-load has been defined as the relatively coarse part of the sediment-load that moves along the stream-bed, and suspended load as the fine part that is distributed throughout the cross-section.

During the past 30 years, many formulas for the rate of transportation in terms of various flow- and sediment-characteristics have been introduced for bed-load, but little has been done in this respect as to suspended load. On the other hand, research has proposed laws for the distribution of suspended load over a cross-section, but no similar expression has been developed for bed-load. The difference in behavior of the different loads is the main reason for a distinction being made between bed-load and suspended load, even though the definition of the distinction often leads to difficulties. Inconsistencies occur when the bed consists of fine sand, especially when the suspended load is of the same or of a similar mechanical composition as the bed-load, and there is no marked boundary between the two.

Although the same material moves partly in suspension, it is still convenient to make a distinction between the two modes of transportation, because the two loads are measured by different methods. Suspended matter, with few exceptions, is measured in terms of concentration by taking samples of the water carrying the sediment. Bed-load, however, cannot be measured in terms of concentration because close to the bed the movement of sediment and water is uncertain. Instead, the rate of bed-load transportation is determined directly by a suitable trap that permits water to pass through but retains the solids by screens or by locally reducing the water-velocity inside the trap. Obviously the distinction between suspended load and bed-load in most sediment-load data is, in reality, merely a distinction in methods of experimental observation. This distinction was employed by Shaank and Slotboom [6] in their studies of the lower Rhine.

As pointed out, the usual distinction between bed-load and suspended load has serious limitations. Observations in certain streams indicate that it is of even less value when the relatively coarse part of the suspended load moves at rates that can be expressed in terms of the stream-discharge, while the relatively fine part bears no relation whatsoever to discharge. For instance, Vetter [7] found that in the Colorado River all the sizes in suspension that show a relation with discharge are also freely available in the bed.

Soil Conservation Service sediment-load investigations--In formulating a program for the Soil Conservation Service, it was recognized that there was urgent need for extensive information on the factors affecting the transportation of sediment in natural streams. A comprehensive program of research therefore was planned, resulting in the construction of a sediment-load laboratory on the Enores River near Greenville, South Carolina [2]. The most important feature of the laboratory is a new type of control which permits the measurement of the total sediment-load of the river. As in previous studies made on the measurement of the total sediment-load of streams [6], all sediment in transportation could not be measured by any one sampling method.

Two sampling procedures are used in the operation of the control to determine the total sediment-load. One portion of the load, consisting of the relatively coarse fractions moving on or near the bed, is removed hydraulically by pipe-connection and pump from openings in the stream-bed. This material is discharged into a settling tank, from which it is later removed to be weighed and analyzed for particle-size. The remaining portion of the stream-load, consisting of the material that does not pass into the bottom-openings, is determined by suspended-load samples taken with special multiple-unit samplers [for description of sampler see reference 2]. This material is also subjected to an analysis for the determination of particle-size.

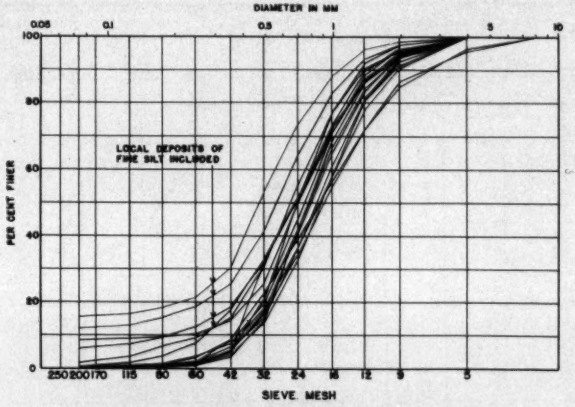

FIG. 1 – AVERAGE COMPOSITION OF BED-MATERIAL ON VARIOUS RANGES ON THE ENOREE RIVER

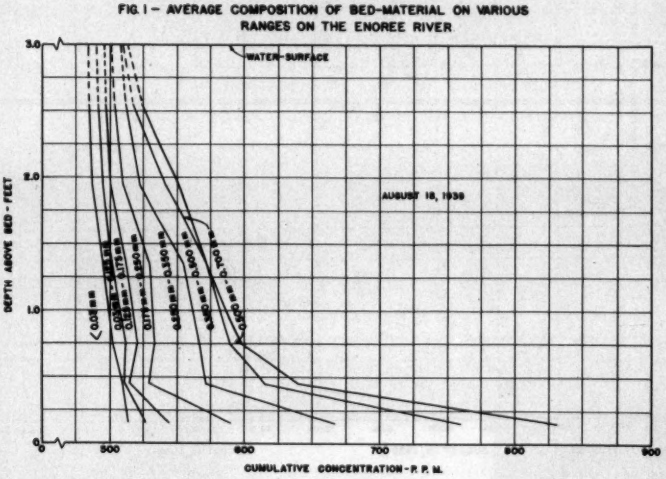

FIG. 2 – TYPICAL SEDIMENT-DISTRIBUTION CURVES IN ENOREE RIVER, S.C.

Several times a year a systematic bed-sampling program is conducted for the purpose of evaluating changes in bed-composition. The procedure of sampling is to scoop a pint container full of material from the bed-surface at four-foot intervals on each of 17 ranges approximately evenly spaced over a 1-1/2-mile reach upstream from the control. The average width of the stream in this reach is 40 feet. Each sample is analyzed for particle-size, and an average mechanical-analysis curve for each range is constructed.

Figure 1, which shows the average mechanical-analysis curves for the various ranges, is typical of the results of a sampling series. Examination of these curves shows that very little material finer than a 42-mesh sieve size (0.351 mm) is available in the bed. A few of the curves, as indicated in Figure 1, show the presence of a considerable quantity of fine material. This fine material was found in samples taken close to the banks and is believed to be the result of local bank undercutting and caving. On the average, however, a break occurs in each curve at

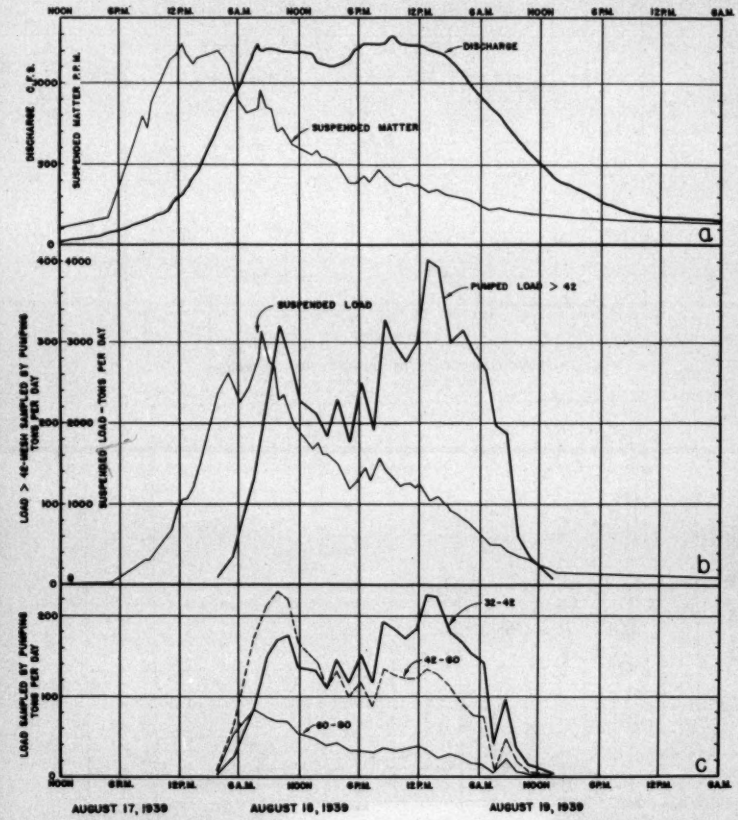

FIG. 3 - DISCHARGE AND SOLIDS-LOAD IN ENOREE RIVER DURING FLOOD OF AUGUST 17, 18, 19, 1939.

the 42-mesh sieve size and indicates that only material coarser than this size is available in the bed in sufficient quantity to be considered abundant. Practically no material finer than the 60-mesh sieve size is found in the bed.

In addition to measurement of sediment-load in the operation of the control, determinations are made of discharge, water-surface slope, dissolved load, rainfall, and water- and air-temperatures. For the purpose of observing changes in the position of the stream-bed, periodic cross-sections are taken on 62 ranges, evenly spaced, over the 1-1/2-mile reach in which samples of bed-material are taken.

Measurements taken during the flood of August 17-19, 1939--A flood of 36-hour duration occurred after a general rainfall of 2.81 inches on August 17 and 1.62 inches on August 18 over the 64.4-square-mile drainage-basin above the control. During this period, sampling of the sediment-load was conducted by the two prescribed methods. A continuous record of discharge was obtained by use of an automatic stage-recorder.

The samples of sediment obtained by pumping were analyzed and the rate of transportation of each size was computed. As suggested by the results of the bed-sample curves (Fig. 1), the rates were summarized for the following typical size fractions: All material greater than 42-mesh sieve; all material passing 32-mesh sieve and retained on 42-mesh sieve; all material passing 42-mesh sieve and retained on 60-mesh sieve; all material passing 60-mesh sieve and retained on 80-mesh sieve.

Frequent samples were taken to determine the average concentration of sediment in suspension throughout the depth of the stream. A typical vertical distribution of various particle-sizes in suspension is shown in Figure 2.

Figure 3a shows a plot of the stream-discharge and the concentration in parts per million of material in suspension. Figure 3b shows a plot of the suspended load and the material coarser than a 42-mesh sieve that is obtained by pumping, both being expressed as a rate in tons per day. The former curve is calculated directly from the curves of Figure 3a. Figure 3c shows the rate of transportation of the various size-fractions mentioned above.

The important features of the various figures may be summarized as follows:

(1) Although there is a general increase in silt-concentration in the river with an increase in water-discharge, the peak silt-concentration precedes the peak water-discharge (Fig. 3a). In the Enoree River the peaks occur in this sequence; although it has been observed in some rivers that occasionally the peak silt-discharge precedes and at other times follows the peak water-discharge, depending largely upon the part of the drainage-area contributing the water and the relative velocity of the water and wave-crest [4].

(2) The rate of transportation of material coarser than a 42-mesh sieve follows a distinctly different curve than that for suspended load (Fig. 3b). (Mechanical analyses showed that the suspended load consisted of material of which 98 per cent is finer than the 42-mesh sieve size.)

(3) With reference to Figure 3c it has been observed that the rate of transportation of material of the sizes ranging between the 32- and 42-mesh sieve follows a curve very similar to the curve (Fig. 3b) for the material coarser than the 42-mesh sieve. On the other hand, material of the size between the 60- and 80-mesh sieve is similar to the curve for suspended load (Fig. 3b). Material of the size between the 42- and 60-mesh sieve size is a transition between the two, but is apparently more similar to the suspended-load curve.

(4) As seen in Figure 1 the average mechanical-analysis curves of the bed-samples from all ranges, except for those samples that include local silt-deposits, show a distinct break at the 42-mesh sieve size and include not more than seven per cent of the material finer than that size.

(5) Particles much coarser than the 42-mesh sieve size are found in suspension, with the coarser fractions more concentrated near the bottom (Fig. 1).

Conclusion--The observations discussed under items (2), (3), and (4) show that the 42-mesh sieve size (0.351 mm) divides the grain-sizes in the Enoree River sediment into two groups. The material in these two groups is transported according to different laws. The grain-size of 0.351 mm is also the lower limit of sizes that are found in the bed in appreciable quantities. It is not a mere coincidence that the break in the mechanical-analysis curve of the bed-material happens to occur exactly at the same grain-size that the law of transportation changes; instead one is the cause of the other. The rate of transportation of material coarser than the 42-mesh sieve seems to be some function of the discharge. The reason for this is that if the flow that enters the reach is not "saturated," enough material is available in the bed to saturate the flow without changing the composition and position of the bed sufficiently to influence the rate of transportation. On the other hand, the material finer than a 42-mesh sieve is not found in

the bed in sufficient amounts to saturate the flow. The material finer than this size, as obtained by suspended-load sampling, enters the stream from the drainage-basin and merely is being carried past the section.

In the Enoree River all material coarser than the size-limit (42-mesh sieve), whether moving on the bed or in suspension, is moved at a rate of transportation that seems to be a function of the discharge. On the other hand, the material finer than the 42-mesh sieve is merely "washed through" the control-section of the river without deposition. No definite relation exists between the load of this fine material and the stream-discharge, as the quantity of material in the stream depends on drainage-basin factors, such as rainfall, runoff, vegetative cover, tillage-methods, and surface and underground storage.

From the preceding discussion it is evident that while the present generally accepted definitions of "bed-load" and "suspended load" classify the total sediment-load in a convenient and easily understood manner from a qualitative standpoint, it is a classification that is of little value in a quantitative study of the transportation of sediment. Realizing the need for a new basis for the classification of the total sediment-load, special analyses of the Enoree River data were made which resulted in the adoption of the following definitions:

BED-LOAD is that part of the total sediment-load composed of all particles greater than a limiting size (42-mesh sieve for the Enoree River) whether moving on the bed or in suspension, and includes all bed-material in movement.

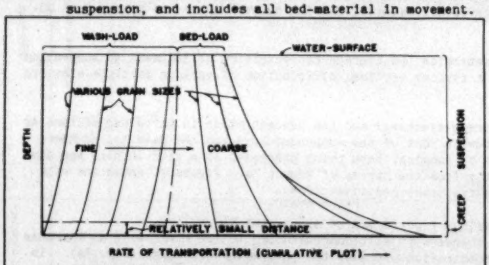

FIG. 4 - ILLUSTRATION OF DISTINCTION BETWEEN THE DIFFERENT PARTS OF THE SOLIDS-LOAD IN A STREAM

WASH-LOAD is that part of the total sediment-load composed of all particles finer than the limiting size (42-mesh sieve for the Enoree River) which usually is washed into and through the reach under consideration.

Bed-material composition is determined from samples taken in the bottom of the channel in the reach under consideration immediately after a flood has receded to the normal low-water stage. Wash-load may enter a river by sheet-wash, bank-caving, and other causes.

The term "suspension" does not relate to the rate of transportation but merely describes the paths of the grains. In research on the transportation of sand by wind, Bagnold [1] contrasted "flying" grains, which correspond exactly to our suspended load, to grains moving by "surface-creep." He divided the quantity transported into two parts, one part consisting of grains flying at a considerable distance from the ground and the other part consisting of grains creeping or rolling along the ground. This distinction can be used to separate material that can be measured in terms of concentration and material that is measured in terms of rate of accumulation in a suitable trap.

Figure 4 shows graphically the distinction between the different parts of the solids-load as proposed by the above definitions. The total solids-load passing a particular section may be considered to consist of two parts, the bed-load and wash-load. The bed-load consists of material moving as surface-creep and material moving in suspension, both of which can be expressed as a rate related to the stream-discharge. The wash-load, on the other hand, moves almost entirely in suspension and bears no relation to discharge. Primarily the conception is that bed-load and suspended load do not supplement each other, as a certain grain may easily be in suspension and still be considered bed-load.

In many past studies on sediment-load transportation in rivers and flumes having the bed-materials of natural sand-mixtures, including those of very fine-size fractions, difficulty in arriving at definite conclusions occurred because no limit was placed on the size of grains that would be included as bed-load. It is therefore suggested that only those grain-sizes should be included in the bed-load whose movement is a function of the hydraulic characteristics of the stream, or conversely, bed-load functions should be applicable only to those grain-sizes which are found in the bed in considerable quantities.

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THE DIFFERENT APPROACHES TO THE STUDY OF PROPULSION OF GRANULAR MATERIALS AND THE VALUE OF THEIR COORDINATION

Paul Nemenyi

Introduction: Varying patterns of flow--The general property of fluid motion which is most striking to me is its shifting character. If we vary only one factor of a well-defined fluid motion problem, for example, if we vary the opening of the flow from a drinking fountain, we can observe a series of phenomena which differ from each other not only quantitatively, but also qualitatively, that is, in their physical nature and appearance.

Let us examine an example somewhat closer to our problem of propulsion of sand and other granular media by fluids: consider the flow of an infinitely broad turbulent stream around a smooth obstacle. The detailed data given here refer to a cylindrical body of infinite length, this being the shape of the obstacle most completely studied to date. We can distinguish five qualitatively different types of flow, each having a fairly well-defined range of Reynolds' numbers (a, b, c, d, e of Fig. 1). The first type is characterized by steady flow, which is of necessity symmetrical with reference to the flow-direction. With increasing Reynolds numbers, it varies continuously from a flow which is almost symmetrical with respect to the perpendicular to the main flow-direction, until a stage is reached where a strong unsymmetry is caused by two oblong vortices in a fixed position in the rear of the obstacle (Fig. 1a). But vortices lose their stability when they are very oblong, decomposing into several vortices, and thus giving place to a double row of vortices. Von Karman showed the instability of a symmetrical disposition of two parallel vortex-rows, explaining why an "antisymmetric" (alternating) pattern of vortices always is found. These antisymmetric vortex-rows in their turn, for obvious reasons, cannot exist in fixed positions with respect to the obstacle, but must travel downstream. Thus we have here the familiar phenomenon of vortices separating from the body alternately at the sides and giving a perfectly regular pattern of vortex-filaments, each parallel to the axis of the cylinder (Fig. 1b). At a certain distance downstream from the obstacle they gradually lose their identity, giving place to an irregular, turbulent flow. As Fage and Falkner showed experimentally, this turbulent wake resulting from the disintegration of the double row of vortices shows a three-dimensional distribution of vorticity and of velocity-fluctuations in spite of the fact that the double row of vortices itself is, within the accuracy of measurement, a strictly two-dimensional phenomenon.

As the Reynolds number increases and approaches 10,000, the "vitality" of the double row of vortices appears to decrease, the turbulent wake coming nearer and nearer to the obstacles. Above R = approximately 10,000, no row of vortices is noticeable, the turbulent wake starting immediately at the obstacle. A closer investigation shows, however, that this turbulent wake continues to be a product of the separation of a laminar boundary-layer just as the double row of vortices. This laminar boundary-layer on the windward side with the "statistically stable" symmetrical turbulent wake on the lee side persists from R equal about 10,000 until R is of the

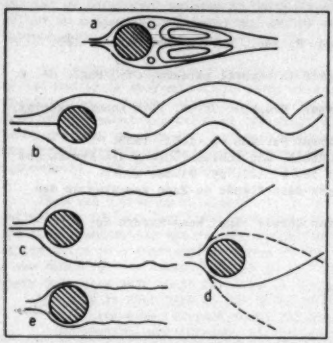

Fig. 1--Various types of flow around a cylindrical body

[All cases for boundary-layer on weather-side: a = laminar, vortices in wake fixed; b = laminar, wake-vortices travel; c = laminar, wake turbulent; d = unstable, turbulent wake in shifting position; e = turbulent, turbulent wake statistically steady]

order of 200,000. (The exact limit between type c and d, as well as between d and e depends somewhat upon the scale of turbulence.)

For any Reynolds numbers above about 500,000, the phenomenon is again a well-known one and has been thoroughly studied. The boundary-layer from which the wake originates is turbulent, as, of course, is also the wake. As experiments show this wake is much narrower, its suction is much weaker than that in stage c.

The transition between these two phases is represented schematically by Figure 1d. This phenomenon was first studied by F. Eisner about 1924 and described in detail in 1929. It was found that the boundary-layer, being in a transitory state between laminar and turbulent flow, is unstable and therefore gives rise to a strongly unsymmetrical wake at either side of the cylinder, the shift from one side to the other taking place at more or less irregular intervals and not directly, but through a short cycle of swinging movements in the rear of the body. (A closely allied phenomenon has been observed also at actual piers of a river-bridge; see the discussion by E. J. Lindley, Trans. Amer. Soc. Civ. Eng., v. 94, p. 1140, 1930.)

The diagram in Figure 2 shows the variation of the resistance-coefficient as a function of Reynolds number. Each different type of flow corresponds to a fairly distinct range of the resistance-curve.

For a sphere the flow-conditions are more difficult to study and to represent. Thus, in spite of very extensive investigations, the phenomena are far less clearly described for the sphere than for the cylinder. So far as our knowledge goes, however, it appears that for the sphere also five different types of flow should be distinguished, each being the axial-symmetric analog of the corresponding type of flow around the cylinder:

(a) Boundary-layer laminar, fixed vorticity in the rear, with strict axial symmetry (vortex-rings) (R from 0 to about 200).

(b) Boundary-layer laminar, separating from the body to give rise to a complicated, but rhythmical, vortex-phenomenon, the double row of vortex-loops gradually dissolving into turbulence (R roughly 200 to 20,000). [In the literature we find often phase b (and sometimes even its two dimensional analog, Karman's double row of vortices) described as "turbulence." However, as recent investigations show, this is inadequate because in spite of the haphazard fluctuations of the undisturbed stream, from which the wake derives its energy, a strict rhythm exists and can be demonstrated by the resonance-method.]

(c) Boundary-layer still laminar, but the row of vortices no longer distinguishable; the statistically stable turbulent wake starts at the body-surface (R about 20,000 to an R which depends upon the turbulence of the original stream).

(d) Boundary-layer in unstable, transitorial state tending towards turbulence, producing an unsymmetrical turbulent wake in unstable, shifting position.

(e) Boundary-layer turbulent; wake quiet, "statistically stable," and turbulent (much narrower than in phase c).

In the diagram of resistance-coefficient (Fig. 3), all of these phases are fairly distinct from each other except a and b, which appear to be one phase. However, if the settling rate as a function of the diameter is computed from the F(R)-diagram and plotted on logarithmic paper, the distinctness of the two phases becomes fairly obvious. They are still more distinct for actual sand grains. (E. W. Lane has shown that the difference between these two phases offers an explanation for the almost complete absence of fine particles below 1/4 mm in the beds of alluvial rivers, even though they carry great quantities of fine silt in suspension.)

I considered it to be advisable to analyze at some length the phenomena of flow around a smooth sphere for several reasons, although it is a mere element of the entire problem of propulsion of granular materials. First, this comparatively simple problem, governed almost completely

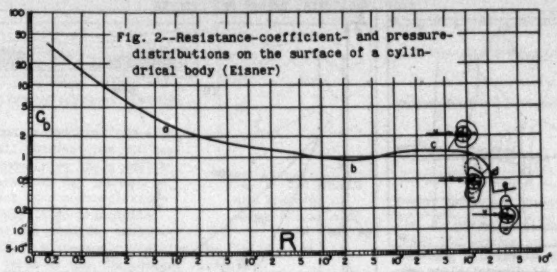

Fig. 2--Resistance-coefficient- and pressure-distributions on the surface of a cylindrical body (Eisner)

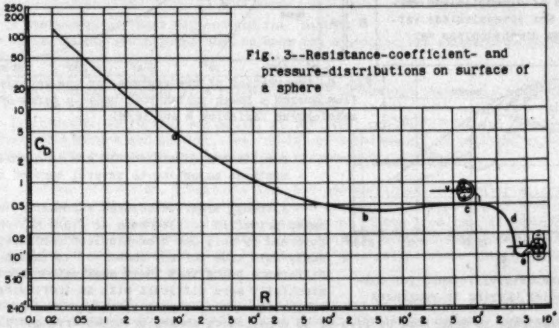

Fig. 3--Resistance-coefficient- and pressure-distributions on surface of a sphere

by only one independent variable, the Reynolds number, exhibits and exemplifies with surprising clarity much of what is fundamental in fluid behavior and recurs in a thousand different forms in almost all problems of fluid mechanics. We see that in spite of the turbulent and statistically steady nature of the flow in its undisturbed state, the boundary-layer on the windward side of the body can be in laminar state as well as in the state of transition towards turbulence or in a stable turbulent state. Further, we see that the laminar boundary-layer may produce, according to its rotor-content, regular vortices in a fixed position or a regular pattern of migrating vortices, as well as turbulence. From turbulent boundary-layers turbulent wakes always are produced while a boundary-layer in the state bordering both laminar and turbulent flow is apt to produce restless, shifting patterns of a stream, with unsteady cycles of transition. With these phenomena as a background, many of the puzzling phenomena of the propulsion of granular media will be better understood.

But also from a methodical point of view the comparatively simple case of a smooth obstacle can give us some important suggestions for handling our more complicated tasks:

(1) For the purpose of approximate empirical study of a quantitative question, several different phases can sometimes be combined; for example, it is possible to give an approximate formula of interpolation for the resistance-coefficient of a smooth sphere or cylinder, covering the phases a, b, c. But even though formulas of this kind may be useful devices for certain practical purposes, they leave many vital aspects of the problem entirely in the dark.

(2) A mathematical theory which describes and mathematical formulas which govern the whole problem are not attainable. At best the single phases, the single types of flow, can be analyzed separately. This presupposes a certain knowledge of their nature which can be gained by experiments. Therefore, qualitative experiments or observations and a descriptive study must always precede attempts toward mathematical theory. The limits between the different types of flow are subject to stability criteria which need a separate investigation.

(3) Extrapolation is a method of generalization upon which in problems of fluid mechanics no reliance whatever can be laid. It may often lead to complete

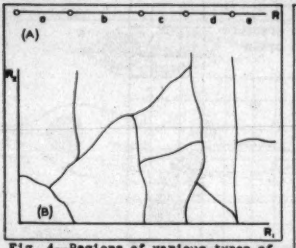

Fig. 4--Regions of various types of flow in terms of dimensionless variables: (A) One dimensionless variable; (B) Two dimensionless variables

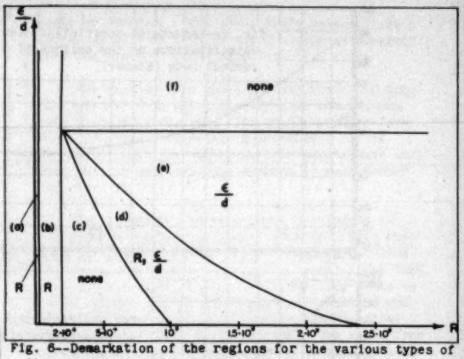

Fig. 6--Demarkation of the regions for the various types of flow around a rough cylindrical body in terms of the dimensionless variables R and (ε/d)

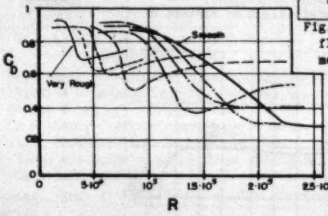

Fig. 5--Resistance-coefficients for cylindrical bodies varying in roughness

qualitative misstatements and to quantitative mistakes amounting to several hundred per cent.

Although these methodical recommendations are based primarily on phenomena of fluid motion which are governed by only one dimensionless variable, they obviously hold true for any number of variables, the only difference being that their application becomes substantially more difficult with an increasing number of variables. While a phenomenon governed by only one independent variable is described by five or so consecutive phases or types arranged along a straight line (see Fig. 4A), two independent variables--we may call them R_1 and R_2--may have a much greater number of distinct flow-types, each corresponding to a part of the (R_1, R_2)-plan, which in general will have curved boundaries (Fig. 4B).

Probably the simplest example of a phenomenon governed by <u>two</u> independent variables is the flow around a <u>rough</u> cylinder, Reynolds number R and the relative roughness (ε/d) playing the rôle of the governing independent variables R_1, R_2. Figure 5 shows some data on the influence of these variables upon the resistance coefficients as given in the recent book of Goldstein [Modern developments in fluid dynamics, edited by Sidney Goldstein, Oxford, 1938]. On the basis of these curves, combined with the curve of Figure 2 and aided by some considerations <u>per analogiam</u>, the author has drawn an approximate "chart" of the main regions of R and (ε/d), each of which corresponds to a distinct qualitatively different type of flow (Fig. 6). It is interesting to see that only within one of these continuous variability both with R and (ε/d) takes place. Within two regions the influence of the latter, if at all present, is negligible; within one, the influence of the former is unimportant; while within two regions neither of both variables causes any considerable change in flow-conditions and resistance-coefficient. Nevertheless no definite statement whatever could be made without using these variables, because the fields within which they do not affect the flow-pattern must be defined as regions of the [R, (ε/d)]-plan. If the number of independent dimensionless variables is <u>three</u>, obviously the regions will be characterized by limited parts of the three-dimensional continuum; and so on.

These considerations may appear at first glance far-fetched or superfluous, but the many and often fruitless controversies and the competing "theories" indicate that strictness in method of representation is of greatest importance.

For example, we find in literature statements to the effect that a considerable amount of fine suspended load tends to increase, to decrease, the water's competence to move heavier sediments; that with the appearance of sand-waves under otherwise unaltered conditions, the relative roughness of a river increases, decreases, remains unvaried; that the ratio (d/r), where r is the hydraulic radius, d is the average grain-size, does give, does not give, direct information about the value of the hydraulic roughness in Manning's formula.

Fig. 7--Sand-waves molded and propelled by vortices (Darwin)

Fig. 8--The growth and breaking of waves (Rosenhead)

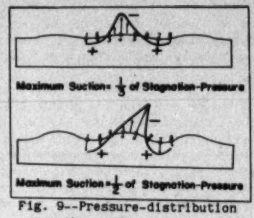

Fig. 9--Pressure-distribution upon the surface of waves according to measurements of Irminger

Our above considerations indicate that all observations and measurements underlying these contradicting statements can perhaps be quite correct, the contradictions being due only to an inadequate statement of the results, particularly a lack of statement concerning the limits of the regions in terms of the independent variables.

Complete statements of these regions and the "mapping out" of the whole problem presupposes that we know the dimensionless independent variables governing the problem.

For a rough circular cylinder or a rough sphere it is obvious that Reynolds number and some kind of a "relative roughness" must play a decisive rôle; but even here a complete study would require the introduction of further variables, at the least one describing the shape or type of the roughness-protuberances and another, the "scale" of turbulence t in relation either to the main dimensions of the body or to the size of the roughness-protuberances.

For the problems of erosion, transportation, and sedimentation of granular materials in rivers the number of variables is obviously very much greater. It might appear therefore at first glance that it would be wise to isolate the study of rivers from that of torrents, of tidal currents in estuaries, of sand-storms in deserts, of aeolian sand-and-snow dunes and allied phenomena, rather than to try a unified study of all these geophysical phenomena in which a granular material is propelled by a fluid in motion.

In favor of this isolationist position the argument may be advanced that while for flow in a pipe or around an obstacle in an infinite fluid dynamic similarity between different fluids is possible--and can in certain cases lead to valuable practical model-arrangements--dynamic similarity between fluvial, torrential, and aeolian transportation phenomena is obviously not possible either in nature or in the laboratory and therefore whatever analogies may exist are bound to be rather superficial, perhaps even misleading.

In spite of the impossibility of strict dynamic similarity it is hoped to show in these pages that the comparative, or, to a certain extent, unified study of all these phenomena not only can be a source of stimulation and of qualitative descriptive ideas, but can even contribute to the creation of a better quantitative method in each particular field.

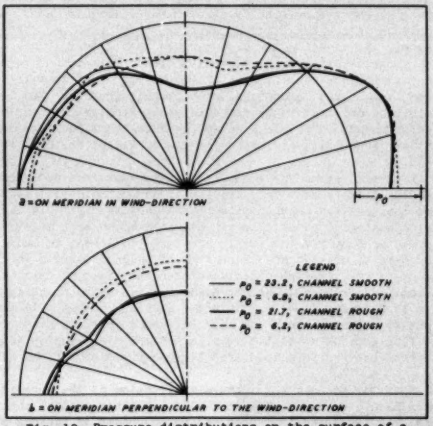
a = ON MERIDIAN IN WIND-DIRECTION
p_0
LEGEND
p_0 = 23.2, CHANNEL SMOOTH
p_0 = 6.8, CHANNEL SMOOTH
p_0 = 21.7, CHANNEL ROUGH
p_0 = 6.2, CHANNEL ROUGH
b = ON MERIDIAN PERPENDICULAR TO THE WIND-DIRECTION

Fig. 10--Pressure-distributions on the surface of a hemispheric mound in per cent of the stagnation-pressure p_0

Comparative study of rhythmic phenomena connected with the propulsion of granular materials--Tendencies towards such comparative or unified studies are not new. The late G. H. Darwin in his famous observations and experiments on ripple-marks of the dune-type investigated both fluvial phenomena and their atmospheric analogs, explaining their shape, growth, and slow migration by the lee vortices which are today generally known (Fig. 7). Inspired by G. H. Darwin's work the English geographer Vaughan Cornish made and assembled a great many obser-

vations on rhythmic forms and their movements, and in 1899 he proceeded to suggest a systematic comparative study of wide scope, namely, "the study of waves and wave-structures of the atmosphere hydrosphere and lithosphere," and proposed to call it with the Greek word "kumatology."

Even if attention is restricted to rhythmic and quasi-rhythmic forms moulded by currents (water-streams and wind) in granular materials, a perplexing variety makes orientation, at first, difficult. Longitudinal dunes, "Seif-dunes," sand-banks, whaleback-dunes, sand-waves proper, ripples (current-marks), barcane-dunes (crescent-dunes), ridges, "transport-deltas," anti-dunes and "erosion-cycles" are a representative but by no means complete list of the denotations encountered. Having, however, examined carefully the major part of the extensive literature of these forms, the author came to the conclusion that essentially three basic phenomena or "mechanisms" are responsible for the origination, transformations and migration of probably all these forms.

(1) The vortex-mechanism in the broadest sense of the word, a generalization of the mechanism described by G. H. Darwin. His original theory does explain, qualitatively, the growth of certain waves and their travel, but not their origin and the great diversity in their form.

Before we discuss these more difficult questions, a few words on the study of wave-growth should be said, because it has been carried in the last 20 years or so far beyond Darwin's results. The mechanism of wave-growth is up to a certain point essentially the same for ocean-waves, for waves in sand and snow, and even for inner waves (density-waves) in currents. L. Prandtl suggested a qualitative theory of wave-growth with the aim to explain the development of a "discontinuity-surface" into an "inner wave" from this into a breaker and finally into a vortex-row; of course, only the first stages of this development are of interest here. Rosenhead followed up Prandtl's suggestion and gave a mathematical analysis of the phenomenon under the assumption of a frictionless fluid. Figure 8 gives the final result of Rosenhead's investigation. More important than the mathematical analysis of the phenomenon is its experimental investigation. Probably the late Danish engineer, Dr. Irminger, who was one of the pioneers in wind-tunnel experiments, was the first to examine the growths of waves on the basis of the study of pressure-distribution. Figure 9 shows the result of his small-scale measurements. It will be seen that even very slight and perfectly symmetrical waves, if a steady turbulent stream is going over them, have an unsymmetrical pressure-distribution which tends to increase the wave-amplitude at the same time bringing a strong unsymmetry into the wave-shape.

While these results give adequate picture and explanation of the most essential features of the mechanism of wave-growth, the claim of their authors that they should explain the generation of waves from a flat surface appears to the author not to be justified. First, because, however slight the originally assumed waves are, it cannot be understood how their rhythm, which is obvious in the longitudinal section, originated and, even more important, it cannot be understood why the crests of the wave-surface should be for many of these wave-forms nearly straight lines perpendicular to the flow-direction. This second point is so much more important because recent turbulence-research has proved beyond doubt that the vorticity in a straight turbulent current is a three-dimensional phenomenon. Therefore the local haphazard suction-centers cannot possibly be expected to be arranged along straight or nearly straight lines. The individual roundish mounds or hillocks caused by such local suctions have to be, therefore, the starting point of investigations concerning the origin of rhythmic form.

Figure 10 shows the author's measurements in a wind-channel on the surface of a hemispheric mound (originally made for purposes of another study). It will be seen that on both sides of this mound the negative pressures (suctions) are incomparably larger than in the rear. In the author's opinion analogous conditions can be expected on more mildly curved mound-surfaces as well and this fact may account for the fairly straight-line crest in many rhythmic formations. It is to the point here to mention an observation of Vaughan Cornish who found that a small sand-hillock is growing in its breadths often more than ten times as fast as the growth of its wave-length is. The mentioned Figure 10 shows, however, also that the relative intensity of this suction at the sides is strongly dependent upon the Reynolds number. In addition the boundary-layer and the intensity of turbulence have some influence upon the pressure-distribution. If we add the long-time fluctuations of flow-direction and the distribution of grain-sizes, we have a sufficient number of factors to account for the great variety of the forms governed by the vortex-mechanism.

The simplest start for the clarification of the genesis of these various forms in wind and rivers should be to examine in a wind- or water-channel the pressure- and suction-distribution on the model-surface of mounds and mound-groups of various shapes and disposition, some simulating the slight, incipient forms and some the more developed, marked ones. Of course, such pressure-measurements in the laboratory, although they can well include various Reynolds numbers,

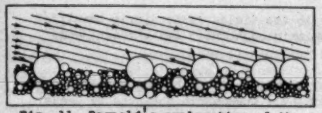

Fig. 11--Bagnold's explanation of the arrangement of a statistical grain-distribution into ripples by low-angle bombardment

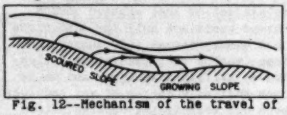

Fig. 12--Mechanism of the travel of an antidune

degrees of turbulence, and boundary-layer conditions, cannot take into account some of the essentials of the real phenomenon, mainly the influence of the gradation of the sand, which is, as has been already shown by Cornish, very significant for these waves. Nevertheless the simple measurements in the laboratory suggested here may supply some very important cues to the dynamic understanding of the great variety of downstream-traveling surface-forms governed by vortices.

Up to quite recent times the vortex-mechanism was considered responsible for practically all rhythmic forms made by wind and for most of those moulded by running water.

(2) The mechanism of low-angle grain-bombardment--In a long series of investigations which are an excellent example for the sound coordination of immediate observation and measurement in the field with experiment in the laboratory and theoretical analysis, R. A. Bagnold has proved that a completely different mechanism can cause the smaller of the rhythms in the desert-sand and indirectly also cooperate in the generation of the larger forms.

The fundamental phenomenon discovered by Bagnold is that the surface of the desert consisting of small and of larger grains up to about 0.8 or 1.0 mm, being bombarded under a low angle by the fine sand of a sand-cloud, is brought by this bombardment from its state of statistical distribution of grain-sizes into a regular rhythmic one because of the shielding of one big grain by its upstream neighbor, the amount of shielding being less if the big grains are farther apart; the greater the distance by which a grain outstrips the one behind, the more hits it will receive and the faster it will roll or creep forward. Thus alternate accumulations of big grains and spaces depleted of them will issue, the spacing being determined by the original gradation of the ground. Thus the incipience of a regular spacing of heaps of coarse sand and with it the wavy form of any section in wind-direction is explained; how the more or less straight wave-front perpendicular to the wind is produced is not discussed by Bagnold. It appears likely that herein the mechanism of vorticity plays a rôle in a manner similar to that outlined under (1).

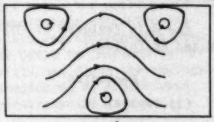

Fig. 13--Exner's theory of serpentines

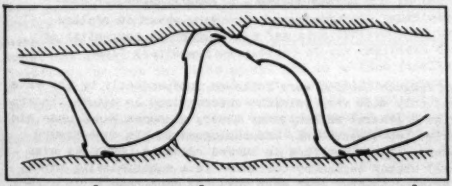

Fig. 14--"Antisymmetric" regular serpentines of Klarälv

Legend
= border of alluvial valley
= deepest parts of bed

As to how the wave-length of the ripples is related to the average or typical saltation orbit of the fine sand-grains; how ripple-mark of this type is formed upon the upstream slope of sand-waves of the larger order, and, in certain cases--of course with opposite direction of travel--on their leeward slope, and many other questions of the forms of sand-propulsion, the work of Bagnold listed in the Bibliography at end of paper should be consulted. It appears that he succeeded in assigning the proper place of the special ripple formation-mechanism discovered by him within the large complexity of aeolian sand-forms in deserts. It should be emphasized that Bagnold's detailed studies proved more conclusively than any earlier work that the character of the gradation-curve, even certain apparently minor features of it, are of definite morphological importance. He showed, however, also that in aeolian sand-dunes along the coast the moisture may have a decisive importance in dune-growth, making all explanations based on observations with dry sand unapplicable.

(3) The mechanism of hindered settling and of steep-angle "hurling" of grains: Antidunes--Many years before G. K. Gilbert observed in the course of his fundamental experiments in the laboratory concerning movement of debris in streams sand-waves with upstream movement occurring if the stream is comparatively shallow and swift (called by him "antidunes"), Vaughan Cornish

had observed the same phenomenon under various conditions in the field--particularly beautiful are his observations made in estuaries on small streams which plough their way through sandy beaches to the sea.

Among the different tentative explanations offered by Cornish, the following appears to be the best: The incipience of the waves can be accounted for by a phenomenon observed by Owens, namely, in a sand-water mixture of considerable concentration the settling velocity of the grains is strongly reduced and, therefore, settling will be stronger where the sand-content is smaller and vice versa. The unstable condition established hereby starts the wave-formation.

As to the upstream travel of the waves, its probable explanation is that erosion occurs here (in contrast to the dune-type waves) on the downstream slope where not only the sand-slope but also the water-slope is much larger. The grains eroded and mostly thrown into suspension here, are thrown under a steep angle against the upstream slope (mostly the immediately following one), these slopes being accreted. Thus the particles travel swiftly downstream and cause the wave-form to travel upstream. This explanation presupposes that no vortices of any considerable strength is present in the wave-trough, an assumption born out well by the observed steep and almost parallel hailing of sand-grains. It seems indeed that neither large-scale turbulence nor vortex-movement plays any rôle in the travel of these waves.

However, many questions remain open. The swiftly developing straight wave-front is unclarified. It is not known either whether the flow is "shooting" (torrential, in the hydraulic sense of this word) or has to be considered rather as in transition-form between quiet and "shooting" flow. This question should be clarified by testing in the laboratory. Still more unclarified is the phenomenon of the paroxysmal occurrence and disappearance of the antidunes (first observed in laboratory by Gilbert and later in a much more marked manner by Pierce in the San Juan River, and by Gottfry Sykes on the Colorado River) and the "erosion-cycles" connected with these phenomena.

The main features of the three basic mechanisms, insofar as they are clarified, may be summarized as follows:

Mechanism	Marked vorticity	Form travels	Occurrence
(1) Vortex	Present in wave-trough	Downstream	Aeolian sand- and snow-forms; sand-form in rivers
(2) Low-angle bombardment	None	Downstream	Sand-ripplies in wind
(3) Antidune	None	Upstream	Sand-waves in shallow water of torrential or transitory flow

Very similar lines of study to those of Vaughan Cornish were followed, independently, by the late Austrian geophysicist F. M. Exner. He not only made very valuable observations in nature concerning mainly coastal dunes but attempted also a general mathematical theory of dunes based upon his conception of "friction-vortices." Likewise two-dimensional, and analogous to his dune-theory, is his mathematical theory of river-meanders. Turbulent flow in curved channels (probably even in straight channels because of the assumed steady secondary currents) is a substantially three-dimensional phenomenon. Therefore this meander-theory, even more than the dune-theory, is a very strong "idealization" and embodies only some of the most important traits of the actual process, making no reliable quantitative predictions possible. Yet even in this primitive form Exner's "mathematical model" of the rhythmic large-scale dune- and meander-phenomena is not without scientific interest. The author considers it as a definite progress in Exner's approach that he includes the serpentine (and meander) in the series of large-scale rhythmical sand-waves. Indeed, there is, I think, more than a merely formal similarity. The serpentine, as well as the migrating dune, is connected with large-scale vortices in a fixed position relative to the migratory alluvial form (and causing its migration), with the only difference that in the serpentine the vortex-axis is nearly longitudinal, while in sand-waves roughly transversal to the water stream-line. This migration in downstream direction is on the average slow in comparison to the fluid motion from which it is caused and affects simultaneously only a limited layer of the granular material. (In this all those waves in granular material which travel downstream differ, as Harold Jeffreys pointed out, very fundamentally from ocean-waves, because in the latter at every instant every particle is in motion.) Finally, serpentines, just like the sand-waves of the dune type--as well as ocean-waves too--show symmetrical forms so long as their amplitude is very small compared with the wave-length, but with increasing amplitude soon developes the characteristic unsymmetry tending toward a "breaker" (Fig. 14).

Grain-study and turbulence-research as fundamentals of the present problem--Valuable though the wave-research in our field is, it has its limitations; the most obvious being that some important and indeed highly effective phases of transportation do not exhibit any definite rhythm. It appears also that in focussing attention upon the wave-forms often two aspects of our problem are not sufficiently taken into account: one is that not only full understanding but even a proper description of propulsion of granular materials, whether it takes place in rhythmic forms or not, presupposes a fairly detailed knowledge of the material itself. The other aspect of our problem which influences, directly or indirectly, all its phases, is turbulence.

"Austausch:" Governing process in higher layers--If we restrict attention to fluid layers sufficiently distant from the boundary their competence to transport material in suspension will be governed as we know from the classic work of Wilhelm Schmidt entirely by the "Austausch"-property of turbulence on one hand by the settling rate of the grain on the other. The mechanism of suspension described by him is exactly the same for a river, insofar as it can be considered straight and infinitely wide, as it is for wind. On the basis of Schmidt's ideas, O'Brien and Christiansen worked out, as well known, a method very valuable for practical hydrology which makes it possible to compute from the velocity-distribution and the tractive force the concentration of suspension of any particular settling rate at any point if it is known by measurement for one point of the vertical. It is recognized now that this theory has--apart from the basic assumption of infinite river-breadth--two weak points: (1) The uncertainty whether the Austausch-function for the different grain-sizes is identical with each other and with that of momentum or whether only proportionality should be assumed; and (2) that the phenomenon of "hindered settling," which is not taken into account, may influence the actual suspension-concentration. I will not expand upon these difficulties which might be easily eliminated by research in the laboratory. I should like, however, before leaving this theory, to call attention to an interesting property inherent in its structure, namely, that the slope does not enter into it as an independent variable in itself, only indirectly, as a factor determining the shearing stress. It follows from this as it can be easily shown, that for two rivers with different slopes but with identical dimensionless velocity distribution-curve $(v/v_{max}) = f(y/y_{max})$, and for which the ratio between the depths is the reciprocal of the ratio between the slopes, the dimensionless concentration-curve for sediments of any settling rate will be also identical. In this unaffectedness by the actual value of slope--a dimensionless variable, which at first glance could be imagined to influence directly the suspension-phenomena--we see with particular clarity how close the analogy of the laws of suspension for very broad rivers is to that for wind insofar as we concentrate attention to the strata not immediately influenced by the bottom respectively the ground.

Search for general variables governing the process of sediment-propulsion--If we proceed from here to the phenomena close to the bottom and to the correlation between composition of the bottom and phenomena in higher layers, we become immediately aware of the incomparably greater complexity of these problems. As the considerations in the introduction of the present paper show, the analysis and systematization of our empirical data, whether they originate from the laboratory or from the field-study, has to be done finally in terms of dimensionless variables $R_1, R_2, R_3, \ldots R_n$. "Regions" in the n-dimensional space defined by these variables correspond to the qualitatively different various types or patterns of the propulsion; while the quantitative data as, for example, total mass of material propelled through a strip of unit-breadth per unit-time, will be written (as Bagnold's considerations suggest) in formulas of the type $f(R_1 \ldots R_n)[V^3(\rho_1 - \rho)/g]$, where ρ_1 = specific mass of grain, ρ = specific mass of fluid, g = terrestrial acceleration, V is a suitably chosen "characteristic velocity" (for example, Bagnold chooses the "bottom shear-velocity"), and where the function $f(R_1 \ldots R_2)$ may have in the various "regions" mentioned widely different character.

However, a strict, formal application of the rules of dimensional analysis to the present problem, is, if possible at all, certainly not practicable. If the number of the various forces influencing a phenomenon is very limited, the rules of dimensional analysis give the number of the independent dimensionless quantities--defined by the π-theorem--and their simplest possible choice. In the present problem, however, quite apart from certain more fundamental difficulties which shall become clearer later, the number of the different factors is too large or indefinite, so that the dimensionless variables would become too numerous to be handled practically. Therefore the problem here is one of a complicated trial and error with the aim of finding the smallest possible number of essentially relevant dimensionless independent variables in terms of which either the problem as a whole or at least a large part of it can be described and analyzed. A good choice will be one which allows the joint study and mutual demarcation of several different "regions," leaving aside only more remote or exceptional realms of the problem.

F. Eisner was the first to make a tentative list of the most relevant independent variables of this problem; his study was made with special reference to the "bed-load" phase. After him,

several authors took up this question [see many items of the Bibliography but particularly 26, 32, 58, 60, 61, 62]. It is, however, still mainly in the stage of hypothesis and controversy, the laborious process of trial and error just having been started. It may be, therefore, fruitful to survey the question from the broad point of view of the present paper, going not only beyond the limitations of the "bed-load" study but also beyond the restriction to rivers.

We consider first (as Eisner did) an individual grain. We will, however, attempt a complete classification of the mechanical forces acting upon a grain (possible electrical forces remain outside this consideration) as basis of our dimensional hypotheses. If the grain is entirely covered by water which is free from air-bubbles, capillary forces are obviously absent. The following appears then to be complete.

(1) Forces exerted upon the grain-surface by the fluid, $F_{(f)}$

(2) Terrestrial gravity--weight of grain--(F_w)

(3) Surface-forces both normal and tangential exerted by other grains (pressure-, friction-, and impact-forces) except those caused by mass-attraction (gravitation) between grains, (F_s)

(4) Forces exerted by other grains in consequence of mass-attraction--cohesional influences--(F_c)

(5) Inertial forces (F_i)

Now the simplest--though by no means the only possible--assumption is that the most relevant dimensionless variables are those which express the importance of each of the active forces (1) to (4) separately relative to the inertial force [force (5)]. In the language of model theory this assumption may be stated as follows: For the complete dynamic similarity of two propulsion phenomena is relevant that the force-ratios (F_f/F_i), (F_w/F_i), (F_s/F_i), and (F_e/F_i) should be the same in both for the corresponding grains. (Instead of force-ratios it is somewhat more convenient to operate with the corresponding energy-ratios; to the inertial forces the kinetic energy is corresponding.)

The result of this analysis does not yield so far new results; it shows, however, how the known results by various authors in different investigations are related to each other.

Indeed the relation of fluid resistance to inertial force leads to the Reynolds number of the grain (vd/ν), introduced by Eisner into bec-load study; as characteristic velocity V he used velocity of the water at the depth where the grain is "mostly" moving. Shields introduced the "shear velocity" $V_* = \sqrt{\tau/\rho}$ as characteristic velocity.

In similar manner the second type of forces leads to the "Froude number of the grain $(V_*^2/dg)[\rho/\rho_1 - \rho)]$. Or in the special case of a river the variable can be expressed in terms of the "tractive force" in the following manner: $(rs/d)[\rho(\rho_1 - \rho)]$, where r is the hydraulic radius and s is the slope. It was in this form that the variable has been used by H. D. Krey many years ago; it is sometimes called "dimensionless tractive force." While Shields' experiments indicate the great significance of both the Reynolds number and Froude number of the grain, in the investigation of certain questions, they can be replaced adequately by one single variable (C/V_*) that is the ratio between the settling rate of the grain and the shear-velocity V_*. This ratio which is a function of the Reynolds number and the Froude number of the grain has been introduced by Lane and Kalinske, who showed that it governs the relationship between bed-sediment and suspended load. A little later, independently, the same was found by Ho. These authors have shown among other things that no particle can be found, in the statistically steady permanent state in suspension for which the above mentioned ratio is substantially greater than 1. How far also the more complicated bottom-phenomena usually characterized as "bed-load movement" can, as a first approximation, be described in terms of this ratio instead of the two numbers of the grain appears not yet to have been investigated.

As to the dimensionless number for the energy-loss by direct contact between grains, it can easily be shown to be $[(w_1^2 - w^2)/w_1^2]$, where w_1 is the velocity of the grain when it arrives at the bottom and w when it starts. If it is assumed that the velocity of the arriving grain is determined by V and can be replaced by it, we have the dimensionless quantity $[(V_*^2 - w^2)/V_*^2] = [1 - (w/V_*)^2]$ or $(1 - B^2)$, where B is the variable introduced by Bagnold in his saltation-studies. How these quantities are related to more fundamental properties of the grain such as their elasticity, size-distribution, and roughness is not clarified.

Even more unclarified is the dimensionless representation of the influence of cohesion. Bagnold demonstrated recently its decisive importance for very fine material, showing the astonishingly high critical tractive force for dry material of extremely small grain-size, even if it is loosely placed in a wind-channel. Meyer-Peter and his coworkers ascribe mainly to cohesion

almost all deviations from the empirical bed-load formula which has been found by them by experiments in water-flume with sand of rather large relative grain-size. This assertion is open to question because, as far as it can be seen from Bagnold's experiments on one hand, from results of soil-mechanics on the other, the cohesion-influence starts to be noticeable only for much smaller grains (probably of the order of 0.1 mm or less, while the Swiss formula ceases to be exact for grains of about 3-mm size); most of the discrepancies may be due predominantly to other forces, mainly to viscosity, the influence of which is almost unnoticeable within the narrow region of variables in which the bulk of the Swiss experiments and observations were made and from which their formula was obtained. Nevertheless the question of cohesion is an interesting one which deserves clarification.

The above tentative considerations which took the dynamics of a single particle as basis for the dimensional analysis face only part of the problem. An equally important part of it is to find out which, if any, of the infinite number of grain-sizes existing in a mixture is dynamically characteristic. It is obvious that no common single rule, valid for all sediment propulsion-problems, can be given as to dynamically adequate replacement of a gradation-curve by a single one of its ordinates. For the comparatively coarse sediment of mountain rivers "d_{35}", (that is, that diameter grains above which represent 35/100 of the total weight) has been found by the Swiss hydrologists to be a more adequate representative of the grain-distribution than the arithmetic mean diameter d_{50}. (However, it can be shown on the basis of the Swiss data that d_{35} is far from representative for the hydraulic roughness--Manning roughness--for the same rivers.) But it is recognized now that, if any degree of general validity should be reached, the gradation-curve has to be characterized by at least two data. Kramer suggested to use arithmetic mean diameter d_{50} and in addition the ratio of the two parts of the gradation-surface on both sides of d_{50}. Krumbein's studies suggest that the geometric mean diameter and the standard geometric deviation of the diameter-distribution (which by aid of a logarithmic scale can be determined with the same ease as the ordinary characteristics) may be more apt for generalizations. To investigations concerning sediment-movement and erosion mainly in their engineering aspects Krumbein's suggestions, which originally were made in view of the studies in sedimentary petrography, were tentatively adapted by H. Rouse.

The problem of finding suitable dimensionless dynamical characteristics for whole grain-distributions is, as will be seen from the above schematic considerations, an extremely complex one and far from its final solution. It involves: (1) Choice and securing of sediment-samples; (2) determination of their geometric and physical properties; (3) suitable graphical and statistical methods for the representation and for the summary-description of the samples; (4) study of dynamically significant test-cases, to find out which of the various possible data describing summarily the sediment-properties should enter into dimensionless characteristics and in which combination with the dynamical data (such as the shear-velocity, etc., of the stream).

The first three phases have gone, in the last ten years or so, a long way in the development towards a complete success. Phase (1) and (2), involving both field- and laboratory-measurements (as well as certain statistical considerations) have been developed mostly in Western Europe and in this country. The phase (3) which is a matter of statistics, geometry, and graphic representation, had recently a strong and important development in this country. It is as true for the present geophysical studies as for the petrographic studies of Krumbein and his coworkers that, although the logarithmic representation of grain-distributions appears to have great advantages, it would be precocious to concentrate upon one single method; various different representations should be developed and used for the same problem in an effort to find out the dynamically most significant summary-data. This decision can be made finally only on the basis of dynamical studies [phase (4)]; but Krumbein points out rightly that the various methods of graphic representation and statistical analysis in addition to their immediate significance, are heuristically valuable. As in petrography they suggest genetic hypotheses in geophysics of sediment-propulsion; they may suggest hypotheses concerning the dimensionless quantities most suitable in our dynamic studies. These very recent American investigations in sedimentary petrography--which include characteristics of the shape of the grain as well as their size--deserve careful study by geophysicists. The sedimentary petrographer's approach is not essentially different from that of the geomorphologist; both want to understand dynamically certain forms and materials of the Earth's crust; but while the morphologist can usually explain them from dynamic processes of our own geologic age (alluvium)--mostly processes still taking place before our eyes--the petrographer has very often to make inferences concerning events in remote geologic ages; the dynamic processes however are fundamentally common. These modern methods of petrographic representation are also an excellent example for unification of sediment-investigation; they are applicable and indeed are applied for sediments of all kinds: Aeolian; fluvial; lacustic; glacial; and shore sediments.

As to phase (4), the investigation of dynamic "test-cases," studies with modern methods are just being started. We will soon return to this question. Here it should be said only that, as, the general consideration given above sufficiently shows, studies in the laboratory alone cannot possibly provide the necessary data for the decision as to the fundamental variables.

Even though it can be hoped that a limited number of independent variables built by aid of two statistically representative properties of the size-distribution of the sediment will characterize a very large field of sedimentary dynamic processes both in water and air, there are certain processes which will resist such a representation. Phenomena connected with covering, protective layers appear to show such an exceptional nature. Many students of river-sediment movement have noticed that the largest particles may have under certain circumstances a decisive rôle in preventing erosion. A recent experiment of Bagnold indicates that, at least in wind, a very minute weight-percentage of heavy pebbles is sufficient to prevent sediment-movement almost completely. Hardly any of the various proposed "characteristic diameters" and "standard deviations" of the grain-distribution would do justice to the rôle played by the largest grains. It is therefore possible that more than two data concerning the size-distribution of a sediment will have to be used in defining the dimensionless variables of the problem if considerable generalizations are attempted.

Sediment-movement as an instance of density-currents--On the other hand, it is also possible that for certain particular processes of sediment-movement an entirely different approach to the dimensional analysis will be adequate. Instead of starting from the individual grain and the forces acting upon it, sand-mixtures of various (or continuously varying) concentrations may be considered and the results of dimensional analysis developed for the study of "density-currents"--a study originating from oceanography--can be applied to them.

Variables specific for the river-problem--While the above considerations are essentially common for all problems of propulsion of granular materials, there are certain phenomena, and certain dimensionless variables corresponding to them, specific for rivers. These are the slope and the variables characteristic for the shape of the cross-section.

The slope has been mentioned already as a factor entering into the "dimensionless tractive force" in the case of rivers. However, under certain conditions it has, in addition, the rôle of a direct independent variable. A careful analysis of the Swiss formula for bed-load movement (Meyer-Peter, Favre, Einstein) shows that this is the case in the realm of relatively coarse sediment for which this formula is valid.

As to the rôle of the shape of bed cross-section and the assumed secondary currents connected herewith, the author has recently started a research of which he hopes to make communications in the near future. Here a few remarks should suffice.

The concept of a "river of infinite breadth" is apt only for purposes of a very rough, first approximation. The use of the hydraulic radius appears preferable to that of an average depth. The concept of hydraulic radius has been given by H. A. Einstein a new interpretation in the light of fluid turbulence. On the basis of this interpretation and of the measured velocity-distribution, the cross-section can be divided into an area "belonging" hydraulically to the bottom and two areas "belonging" to the sides. This distinction is of value for the summary-determination of bed-load quantity in the cross-section of a mountain river, as has been shown recently by the Swiss Federal Authority for Water Utilization. Closely allied, but much more far-reaching are the suggestions of John B. Leighly, who attempts to determine from the actual velocity-distribution the distribution of the Austausch-coefficient throughout the whole cross-section as well as the distribution of the tractive force along the wetted perimeter. The principle established by Leighly is of great dynamic and morphologic significance. The Austausch-distribution received by him appears to be, in spite of certain minor geometrical mistakes in his graphical method, at least qualitatively correct; its qualitative agreement with the Austausch-distribution found by Hjulström by an entirely different process is remarkable.

However, although the actual Austausch-distribution may be in straight river-reaches the most important single clue for the explanation of morphological changes, it does not follow that as Leighly assumes other factors, such as the steady secondary currents, are insignificant. These currents, the existence of which is today almost generally admitted although their shape is still unclarified, have not only an indirect importance because of their interdependence with the distribution of longitudinal velocities, but also an appreciable direct influence upon the distribution of the finer particles. In curved river-reaches the steady secondary current in the cross-section may have even as great a direct influence as the Austausch itself.

Dynamic test-cases--The above tentative outline of the factors which govern sediment-movement indicated not only the present unsettled state of these studies but also their inherent fundamental difficulties. Not only the limitations of mathematical hydrodynamics and of fundamental experimentation in laboratories have been pointed out but it has been shown also that the formal rules of dimensional analysis are not applicable to the present field as a whole, that to the contrary the basic dimensionless variables, which are expected to bring order and system into the vast variety of propulsion phenomena, have to be discovered first in the process of many tentative representations and comparative studies of actual data concerning the motion of fluid and the sediment propelled. In principle, any data as they come from geographical, hydrological, or engineering observations and measurements, are apt material for this study. The above inquiries indicate, however, that the greatest progress in our problem can be expected by the proper choice and comparative analysis of "dynamic test-cases."

For purposes of fundamental research, test-cases should always be as simple as possible. The first obvious sources are engineering objects connected with sediment-movement such as irrigation-canals, foots of weirs, bridge-piers, etc. Observations of sediment-processes at such objects are useful for fundamental research if conditions are comparatively simple; their value is increased if records concerning experiments in the laboratory for the object in question (preferably on undistorted models) are available for comparison. (Distorted models are indispensable in certain engineering problems and they have been recently developed to considerable practical perfection; they appear to be however more difficult in application to the fundamental research here in question because--although they may yield very good inferences as to certain particular quantitative questions--they are often inevitably very remote from a complete dynamic similarity to the prototype.)

Characteristic river-reaches as dynamic test-cases for the laws of sediment-propulsion--Even more important test-cases are found, however, in rivers, shore-lines, sand-dunes, and other geographical objects if they are entirely untouched by human interference, and if geological conditions are particularly simple (oblique stratification, etc., absent). Many reaches of rivers and streams which are "alluvial in the stricter sense of the word" (that is, flowing in an alluvial bed built up by the same river or stream under hydrographical conditions similar to those prevailing at present--definition of Meyer-Peter and the Swiss Federal Authority of Water Utilization) satisfy these conditions and among them a selection of the most regular straight reaches, serpentines, meanders, typical braided reaches, and deltas should be made, studied, and collated statistically. Morphological studies and statistics of particularly well-shaped river-reaches, mainly of meanders, has been made towards the end of the last and early in the present century by Vujevic, Jefferson, and others--probably the most careful of these studies were those which Steen de Geer made in Sweden, particularly on the Klar Elv. However, although they made an important contribution to geography, they did not yield any deeper insight into the basic variables determining the development of an alluvial river. Today with our deeper, more-advanced knowledge of the fundamentals of fluid mechanics on one hand, with an incomparably more-advanced technique of securing, analyzing, and representing sediment-data, as well as hydrometric and hydrographic information on the other, these studies should be reassumed and can yield no doubt not only decisive general laws about the conditions under which anyone of these forms can be expected, but also about the fundamental variables which underlie these conditions. Experiments in the laboratory being insufficient because of the inadmissibility of extrapolation and ordinary data, as they come, being difficult to handle because of their extreme complexity, we should expect the greatest progress from a many-sided examination of those full-scale phenomena in the field which, thanks to a fortunate combination of circumstances, are as regular and lucid as if they would take place under controlled conditions.

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THE THEORY OF GROUND-WATER MOTION

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(Abstract)

The existing analytical treatments of ground-water flow have mostly been founded upon the conception of limited validity, borrowed from the theory of the flow of the ideal frictionless fluids of classical hydrodynamics, that ground-water motion is derivable from a velocity-potential. This conception is in conformity with the principle of the conservation of matter but not with that of the conservation of energy. In the present paper it is shown that a more exceptionless analytical theory results if a potential whose value at a given point is defined to be equal to the work required to transform unit-mass of fluid from an arbitrary standard state to the state at the point in question, is employed. Denoting this function by Φ, it is shown that the differential equation of fluid flow in an isotropic medium is given by $\mathbf{q} = -\sigma \operatorname{grad} \Phi$, where $\mathbf{q}$ is the flow-vector whose magnitude is equal to the volume of fluid crossing a unit of area normal to the flow-direction in unit-time, and σ a specific conductivity-parameter depending upon the properties both of the fluid and of the medium. This is an expression of Darcy's law and is physically, as well as mathematically, analogous to Ohm's law in electricity and leads to the same deductions in analogous situations.

It is shown that $\sigma = (k\rho/\eta)$, where k is the permeability-parameter depending upon the geometrical properties of the medium only, and ρ and η are the density and viscosity, respectively, of the fluid.

The remainder of the paper is devoted to deducing the consequences of Darcy's law as expressed above with particular regard for the practical problems of ground-water hydrology.

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PRESENT STATUS OF OUR KNOWLEDGE REGARDING THE HYDRAULICS OF GROUND-WATER

O. E. Meinzer and L. K. Wenzel

(Abstract)

Darcy's law, that the flow of water through porous materials increases directly as the hydraulic gradient, has been given much investigation. Investigations made in the Hydrologic Laboratory of the United States Geological Survey show that Darcy's law holds down to a gradient of two or three inches to the mile, and there are indications that it holds to less than one inch to the mile. On the basis of the work of Tolman and Poland it is evident that Darcy's law applies to the movement of ground-water under high gradients and high velocities except under very unusual conditions. It is now clear that Darcy's law applies to laminar flow, in which essentially no energy is lost in producing eddies.

The rate of movement of the ground-water has been determined at many places--directly by the use of salts or dyes or indirectly from determinations of permeability. In field-tests, rates of movement of as much as 420 feet a day have been found. The lowest rate in the Hydrologic Laboratory was about one foot in ten years. In nature the range is doubtless even greater. However, in the recognized water-bearing formations, from which the wells obtain their water-supplies, the natural rate of movement of the ground-water is generally not greater than five feet a day and not less than five feet a year.

The energy that keeps ground-water in motion against internal friction created by its own viscosity is provided by the difference in head between the place of intake and the place of discharge. The hydraulic gradients are three-dimensional, and the water moves not only along the water-table but also to depths below the water-table and generally upward again to the water-table at some other place. In stratified formations the water moves chiefly parallel to the stratification through the most permeable beds but movement through the confining beds is an important factor in the recharge and discharge of artesian aquifers.

Until rather recently it has been tacitly assumed that artesian systems are rigid. Under such conditions changes in head would be transmitted quickly, as no transfer of water would be involved except the small amount due to the slight volume-elasticity of the water. It is now

known that artesian systems possess volume-elasticity and hence variations in storage-capacity with changes in the internal buoyant force due to changes in head. Presumably the compression, and also the reexpansion, occur largely in the strata of relatively fine grain which feed into the strata of coarser grain that supply the wells. The phenomenon of volume-elasticity has been given mathematical study by C. V. Theis [Trans. Amer. Geophys. Union, pp. 519-524, 1935], who applied the theory of the flow of heat to the problem. Recently Jacob attacked the same problem directly with hydrologic concepts without recourse to the analogy of heat [On the flow of water through an elastic aquifer, Trans. Amer. Geophys. Union, pp. 574-586, 1940].

Dupuit apparently was the first to apply Darcy's law to the hydraulics of wells. He developed the widely known equilibrium-type formula which, however, is strictly applicable only to circular islands. Thiem apparently was the first to employ the Dupuit formula for determining permeability of water-bearing formations by utilizing the drawdown of the water-levels in two observation-wells. Theis was the first to introduce the non-equilibrium formula for determining the drawdown of the water-level at any time and at any place on the cone of depression. This formula applies to the non-uniform flow of ground-water, in contrast to the equilibrium-type formulas which do not.

There are four different groups of methods for determining the permeability of water-bearing materials: (1) Direct laboratory-methods; (2) indirect laboratory-methods; (3) field-velocity methods; and (4) field-discharge methods. There are now in use in the United States Geological Survey a number of interrelated field-discharge methods which are expressed by formulas designated as the Thiem formula and associated limiting formula, the gradient-formula, the non-equilibrium formula, and the recovery-formula. The first two of these formulas belong to the equilibrium-type and the last two belong to the non-equilibrium type.

Natural earth-materials tested in the Hydrologic Laboratory of the United States Geological Survey have been found to have coefficients of permeability that range from about 0.0002 to about 90,000 (Meinzer's coefficient), that is, the most permeable material carries water at a rate of about 450,000,000 times that of the least permeable. However, most water-bearing materials utilized by wells have coefficients that are whole numbers of two or more figures, generally between 10 and 5,000.

[Note--The complete paper will be published in a forthcoming issue of Economic Geology.]

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SYNTHETIC UNIT-HYDROGRAPHS, DISTRIBUTION-GRAPHS AND FLOOD-ROUTING IN THE UPPER OHIO RIVER BASIN

N. R. Laden, T. L. Reilly, and J. S. Minnotte

A comprehensive flood-runoff and flood-routing study, believed by the authors to be of greater scope and detail than any previously made, has been undertaken recently by the United States Engineer Office, Pittsburgh, Pennsylvania. The study involves, in general, the selection of a flood-routing method deemed most suitable for use in the upper Ohio River Basin and the application of the method to 17 actual and hypothetical floods to determine flood-control reservoir-effects. The area embraced in the study is that of the Pittsburgh Engineer District and includes 25,325 square miles above Powhatan Point, Ohio.

Preliminary studies have indicated the "coefficient-method" of flood-routing, first developed in the United States Engineer Office, Muskingum, Ohio, in 1933, to be the most practical for the purpose outlined. Credit for the development of this method belongs to Frank B. Harkness and Gerald T. McCarthy.

The authors are not prepared at this time to discuss in detail the results of the actual flood-routing except to say that they are entirely satisfactory. It is their intention to present, in a later paper, a more detailed discussion of the results obtained, certain conclusions reached, and definite recommendations with reference to the application of the flood-routing method employed.

At the present time, however, the authors desire to present an outline of the methods used in determining the unrated tributary-inflows.

The floods selected for routing date from March, 1907. For many of the tributary-streams no discharge-records have ever been published; for others, the stream-flow record is short or intermittent. In many cases, the published record consists only of once- or twice-daily gage-readings. For many stations a rating curve is non-existent or poorly defined. For some floods and in many areas, the rainfall-records are not available or are inadequate.

However, in spite of the lack of basic data and the apparent magnitude of the task, it was necessary to compute unit-hydrographs and distribution-graphs for eight-hour storm-periods (the routing interval selected) for all streams tributary to the 15 routing reaches (see Fig. 1). The manner in which this was done is discussed in the paragraphs following.

Description of plates and tables--Figure 1 shows the drainage-basin limits of the Pittsburgh Engineer District and the limits of the flood-routing reaches.

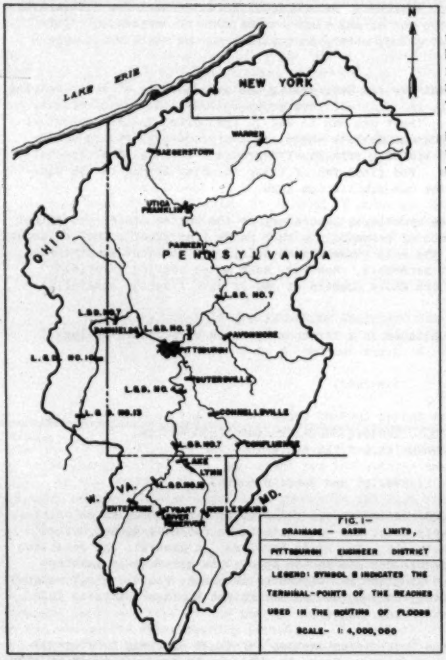

Figure 2 shows the mass-distribution curves developed from the unit-hydrographs. They are curves of best fit, and best approximate the variable results obtained.

Figure 3 shows the relationship between the base of a unit-graph to the peak-discharge for watersheds of various shapes.

Table 1 lists all the rated watersheds in the Pittsburgh Engineer District for which the necessary hydrologic studies were made, together with drainage-basin characteristics of the various areas.

Source of precipitation- and discharge-data: Precipitation-data--Prior to October, 1937, most of the available rainfall-data were those furnished by cooperative Weather Bureau observers who made observations once a day. More complete records were obtainable for gages located at river-navigation dams where lock-masters made thrice-daily observations, and for the Weather Bureau stations located at Pittsburgh and Erie, Pennsylvania, and Elkins, West Virginia, where clock-hour, continuous records are taken. The preponderance of the former stations made the construction of mass-rainfall curves, for the determination of eight-hour incremental rainfall, difficult.

Discharge-data--Most of the discharge-data were based on staff or chain-gage observations taken once or twice daily, supplemented by more frequent readings during flood-stages. A few of the watersheds had automatic recorders but their period of record was relatively short.

Method of obtaining distribution-graphs when unit-storms are not available--The derivation of the distribution-graph for Oil Creek, above Rouseville, Pennsylvania, will be used as an example of the procedure followed. The precipitation from the storm of March 4-6, 1938, on Oil Creek, fell in 16 hours and resulted in a natural hydrograph with surface -runoff lasting 126 hours. Tabulation-sheet A indicates the steps in the development of the distribution-graph for the watershed.

Column (5) with percentage plotted as ordinates against time, in hours, would be the distribution-graph, while column (6) with accumulative percentage as ordinates against time in hours

produces the summation or mass-distribution graph hereafter termed the S-curve, due to its shape. This curve may be used to construct a distribution-graph for any unit-time interval greater or less than that used to determine the distribution-graph. The distribution-graph of the Oil Creek Area, derived from a storm of 16 hours, may then be used to obtain the distribution-graph for an eight-hour storm by the method described in a later paragraph.

Summation or mass-distribution graphs--The procedure outline for deriving mass-distribution graphs for eight-hour storms from those developed for longer storms is illustrated herewith, using

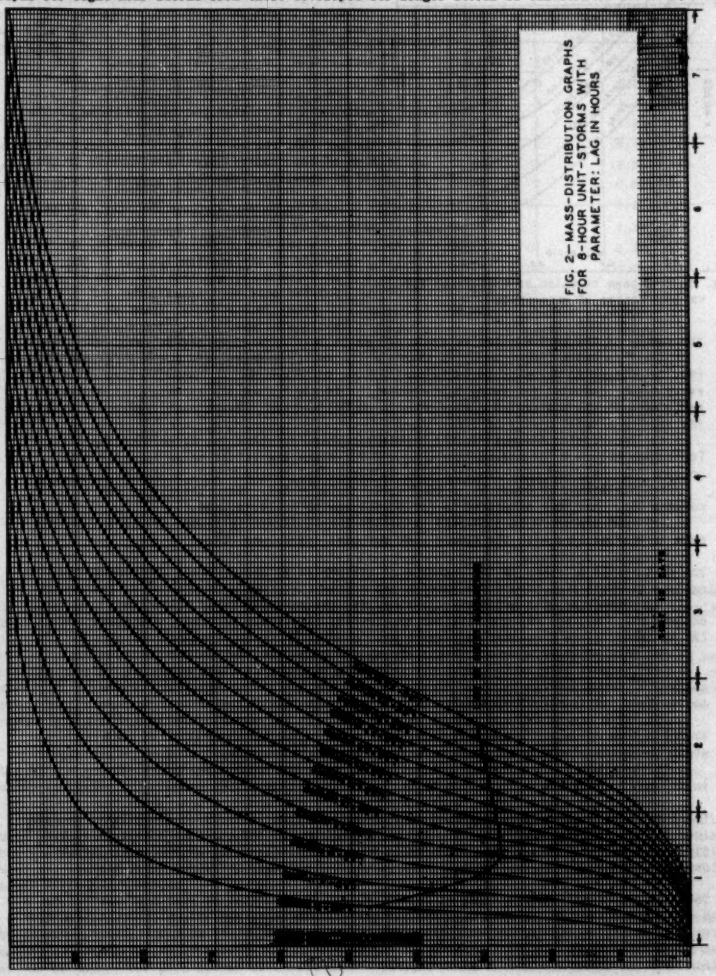

FIG. 2—MASS-DISTRIBUTION GRAPHS FOR 8-HOUR UNIT-STORMS WITH PARAMETER: LAG IN HOURS

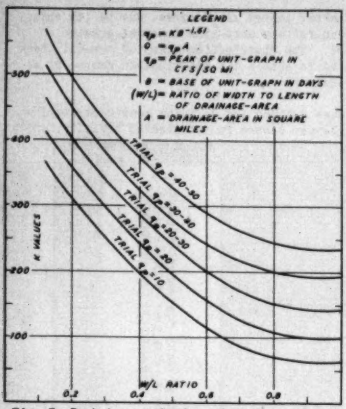

Fig. 3--Peak-base relation of unit-graph for various shapes of watersheds

as an example the graph for Redbank Creek at the flood-control dam-site.

The original distribution-graph for Redbank Creek was derived from 12-hour storms. The summation of these distribution-graph percentages, set off in six-hour intervals, are combined analytically to yield the mass-distribution graph percentages, in six-hour periods, for a 24-hour storm (see Tabulation-sheet B). This is simply half the sum of two mass-distribution graphs for two 12-hour unit-storms, 12 hours out of phase.

The mass-distribution graph for the 24-hour unit-storm is plotted and the ordinates at the beginning of each four-hour period (the shorter the periods, the more accurate will be the definition of the desired curve) are entered in column (2) of Tabulation-sheet C.

The values for columns (3), (4), and (5) are obtained as follows:

(a) The values of column (3) are obtained by subtracting the sum of the values of columns (4) and (5) from that of column (2) for each horizontal line.

(b) In horizontal space No. 1 (the horizontal spaces are here equivalent to the number of the period), the value in column (3) will therefore become zero.

(c) This value (here, zero) is then simultaneously entered into columns (4) and (5), but staggered downward to horizontal spaces No. 3 and No. 5, respectively. Thus, every figure computed for entry into column (3) is simultaneously repeated but depressed two places in the horizontal spaces of columns (4) and (5). Hence each figure of column (3) appears a total number of three times.

(d) Progressing downward in the Tabulation-sheet to space No. 2, we find the $\{0.7$ [of column (2)] - 0 [of column (4 + 5)]$\}$ = 0.7. Hence the latter value is entered in columns (3), (4), and (5), respectively, in horizontal spaces No. 2, 4, and 6.

(e) Similarly, in space No. 3 [6.7 - (0.7 + 0)] = 6.0. Note the figure 6.0 in columns (3), (4), (5), staggered to horizontal spaces No. 4, 6, and 8.

(f) This procedure is continued until the lowest figure in column (5) is in the same horizontal line with the figure "100 per cent" of column (2).

The next series of steps is the converse of the preceding calculation, the computations proceeding from the bottom of Tabulation-sheet C and continuing upwards to the top of the sheet.

(a) Commencing with horizontal line No. 44, the numerals to be posted in columns (7), (8), and (9) are obtained by dividing the "100.0 per cent" of column (2) by three, since a 24-hour unit-graph will consist of three eight-hour graphs.

(b) This value is inserted in all the spaces below the heavy black lines.

(c) The next step is to derive the values for column (9). All values of column (9), when once computed, are repeated upwards in the two adjacent columns to the left. This might be exemplified by horizontal line No. 43.

(d) [99.9 per cent (in column 2) - 66.7 (which is the sum of 33.3-1/3 and 33.3-1/3 from columns (7) and (8)] = 33.2 per cent. Note the repetition of 33.2 above the heavy black lines. This process is continued upwards.

(e) As a check, it should be noted that for any horizontal line the values in column (3 + 4 + 5 + 7 + 8 + 9) = twice the value in column (2).

The last step involves the derivation of values for column (6). These constitute two sets of values for the eight-hour unit-storm. The upper figures in this column are calculated by multiplying the values in column (3) by three to bring the total summation-percentage to 100. The lower figures are the percentage-values in column (7) and also increased three times.

The mass-distribution percentages of column (6) are then plotted at four-hour intervals. A smooth curve drawn through the mass-distribution percentages of column (6), plotted at four-hour intervals, will define the desired mass-distribution graph for an eight-hour unit-storm. Distribution-graph percentages for any time-interval may be obtained from this curve. A graphical solution of this same problem may also be usefully employed, especially where the initial distribution-graph results from periods of unequal rainfall.

Tabulation-sheet A--Steps in development of distribution-graph for Oil Creek Watershed

Time in hours after beginning	Surface-flow inst. peak	Average surface Q	Volume day-sec-ft during interval	Per cent of total volume	Accumulative per cent	6-hour period	Average distribution-graph per cent in 6-hour periods for 16-hour storms
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0	0		0	0	0	1	1.95
4	610	0	51	0.59	0.59	2	6.20
12	3240	305	646	7.42	8.01	3	11.91
19	5800	1925	1294	14.87	22.88	4	17.80
21	6060	4420	495	5.69	28.57	5	16.45
22	6100	5830	253	2.91	31.48	6	12.90
24	6100	6080	509	5.85	37.33	7	8.30
26	6050	6100	506	5.82	43.15	8	5.40
28	5880	6075	497	5.71	48.86	9	4.20
30	5480	5965	474	5.45	54.31	10	3.30
35	3600	5680	945	10.86	65.17	11	2.60
44	2125	4540	1072	12.32	77.49	12	1.95
50	1425	2862	444	5.10	82.59	13	1.60
54	1215	1775	220	2.52	85.11	14	1.40
60	980	1320	274	3.15	88.26	15	1.20
68	760	1097	290	3.33	91.59	16	1.00
82	460	870	356	4.09	95.68	17	.75
92	315	610	161	1.85	97.53	18	.40
100	225	387	90	1.03	98.56	19	.38
108	160	270	64	.74	99.30	20	.22
114	100	192	33	.38	99.68	21	.09
120	50	130	19	.22	99.90		
126	0	75	6	.10	100.00		100.00
		25	8700				

The theory of the unit-graph implies that a drainage-area runoff resulting from unit-rains, if continued indefinitely, will produce a flood whose peak will remain stationary after complete surface-runoff is obtained from the first unit of rain.

A rapid check on the mass-distribution percentages for a given watershed can therefore be made by combining consecutively a number of eight-hour unit-storms into one of two- or three-day duration. The peak-discharge of the resultant unit-hydrograph, instead of occurring instantaneously will remain at some definite magnitude for several eight-hour periods. The greater the number of unit-storms so combined, the flatter the resultant curve will appear at its summit.

Tabulation-sheet D is a sample computation for a drainage-area of 125 square miles and a lag of six hours. The mass-distribution percentages were selected from the family of curves shown in Figure 2 for a lag of six hours.

In the first portion of the tabulation the unit-storm is combined three times. The resultant peak-discharge is still instantaneous. The new storm is then compounded five times. In the last column, the values represent the discharges for eight-hour periods, for the original unit-storm augmented 18 times in duration. The resultant peak-discharge is maintained for seven eight-hour periods.

Existing methods for determining synthetic graphs--Gerald T. McCarthy, from investigations based on a study of topographic characteristics of Connecticut River tributaries, developed a series of nomographic charts for obtaining the elements of unit-hydrographs [see 1 of "References" at end of paper] for unit-storms of twelve-hour duration. This method was tried out on several

Tabulation-sheet B--Derivation of summation or mass distribution-graph in six-hour periods for a 24-hour storm for Redbank Creek

No. of 6-hour periods	First 12-hour storm accumulative per cent	Second 12-hour storm accumulative per cent	Sum (1) + (2)	24-hour storm accumulative per cent	No. of 6-hour periods	First 12-hour storm accumulative per cent	Second 12-hour storm accumulative per cent	Sum (1) + (2)	24-hour storm accumulative per cent
(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
1	0		0	0	17	93.4	90.9	184.3	92.2
2	5.0		5.0	2.5	18	94.5	92.2	186.7	93.4
3	21.0	0	21.0	10.5	19	95.5	93.4	188.9	94.5
4	42.9	5.0	47.9	24.0	20	96.4	94.5	190.9	95.5
5	58.9	21.9	79.9	40.0	21	97.2	95.5	192.7	96.4
6	66.7	42.9	109.6	54.8	22	97.9	96.4	194.3	97.2
7	72.1	58.9	131.0	65.5	23	98.5	97.2	195.7	97.9
8	76.1	66.7	142.9	71.5	24	99.0	97.9	196.9	98.5
9	79.5	72.1	151.6	75.8	25	99.4	98.5	197.9	99.0
10	82.2	76.1	158.4	79.2	26	99.7	99.0	198.7	99.4
11	84.4	79.5	163.9	82.0	27	99.9	99.4	199.3	99.7
12	86.3	82.2	168.5	84.3	28	100.0	99.7	199.7	99.8
13	88.0	84.4	172.4	86.2	29	100.0	99.9	199.9	99.9
14	89.5	86.3	175.8	87.9		100.0	100.0	200.0	100.0
15	90.9	88.0	178.9	89.5		100.0	100.0		
16	92.2	89.5	181.7	90.9					

model areas in the upper Ohio River Basin, that is, areas where unit-graphs were developed from discharge-data. Quite aside from the tediousness of the method, it was found that the distribution-graph percentages developed from McCarthy's nomographic charts gave computed hydrographs with peaks lower than those observed. This indicates that for the Allegheny and Monongahela basins probably the governing topographic indices of a drainage-area affecting runoff are not alone the slope of the area-elevation curve and stream-pattern, but of some additional factor or factors. Another limitation to the use of this method is that the hydrologic relations developed by Mr. McCarthy apply to areas less than 800 square miles.

Franklin E. Snyder [2], using unit-graph data developed from rated streams in the Tennessee River Basin has presented a method for obtaining unit-hydrograph on unrated areas by the device of setting forth other topographic indices against the various elements of the unit-graph (peak, volume, and base). The principal index used by Mr. Snyder is the lag, defined as the time between center of mass of surface-runoff producing rain of a specified type of storm, and the peak of the unit-graph.

The limitations of this method are (1) the relatively wider range of the constants for determining lag and peak, respectively, in this District than in the one where Mr. Snyder's studies were made and (2) the unreliability of transposing his constants for the determination of the base of the unit-hydrograph and duration of the unit-storm, that is, unit-graphs applicable to six-hour, eight-hour, twelve-hour, etc., storms.

Method adopted--In general, the method adopted resolves itself into a combination of the Snyder and McCarthy methods to develop data derived from rated watersheds of varying physiographic and topographic characteristics, and transposition of these data to unrated areas.

Mr. Snyder's formula [2] for lag is as follows: $lag = C_t (L \quad Lca)^{0.3}$ where L is the length of the stream above the point under consideration, and Lca is the distance to the center of gravity of the watershed, measured along the main stream. It was assumed in this current study that the exponent of 0.3, derived from the Appalachian Mountain Region of Tennessee, would not vary much when applied to areas of known lag on the Allegheny and Monongahela basins. The problem of developing lags for unrated areas then resolved itself into the determination of the proper value of the lag-coefficient, C_t. In the case of the larger tributaries, of which some upstream portion was rated and the lag determined, the coefficient C_t was computed. This value was subsequently applied to the entire basin if the lower reaches of the river had similar channel-slopes, land-slopes, width-to-length ratio or shape, stream-pattern or density. In cases where no portion of the area was rated, the coefficient for lag was transposed from the unit-graph of a rated area,

Tabulation-sheet C--Derivation of summation or mass distribution-graph in 4-hour periods for a 24-hour storm for Redbank Creek

No. of 4-hour periods	24-hour storm accumulative per cent	See text for derivation of columns (3), (4), (5)			8-hour storm accumulative per cent	See text for derivation of columns (7), (8), (9)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
					0			
1	0	0			0			
					2.1			
2	0.7	0.7			1.5	0.5		
					7.5			
3	2.5	2.5	0		10.8	3.6		
					18.0			
4	6.7	6.0	0.7		20.4	6.8	0.5	
					32.4			
5	13.3	10.8	2.5	0	32.7	10.9	3.6	
					51.9			
6	24.0	17.3	6.0	0.7	50.1	16.7	6.8	0.5
					62.7			
7	34.2	20.9	10.8	2.5	59.1	19.7	10.9	3.6
					65.1			
8	45.0	21.7	17.3	6.0	64.5	21.5	16.7	6.8
					69.3			
9	54.8	23.1	20.9	10.8	72.6	24.2	19.7	10.9
					70.5			
10	62.5	23.5	21.7	17.3	72.9	24.3	21.5	16.7
					72.0			
11	68	24.0	23.1	20.9	72.3	24.1	24.2	19.7
					79.5			
12	71.7	26.5	23.5	21.7	77.7	25.9	24.3	21.5
					82.5			
13	74.6	27.5	24.0	23.1	78.9	26.3	24.1	24.2
					81.3			
14	77.1	27.1	26.5	23.5	80.7	26.9	25.9	24.3
					79.2			
15	77.9	26.4	27.5	24.0	82.5	27.5	26.3	24.1
					82.5			
16	81.1	27.5	27.1	26.5	84.9	28.3	26.9	25.9
					86.4			
17	82.7	28.8	26.4	27.5	86.7	28.9	27.5	26.3
					89.1			
18	84.3	29.7	27.5	27.1	87.3	29.1	28.3	26.9
					91.5			
19	85.7	30.5	28.8	26.4	87.9	29.3	28.9	27.5
					89.1			
20	86.9	29.7	29.7	27.5	88.5	29.5	29.1	28.3
					86.1			
21	88.0	28.7	30.5	28.8	89.4	29.8	29.3	28.9
					88.8			
22	89.0	29.6	29.7	29.7	91.2	30.4	29.5	29.1
					92.4			
23	90.0	30.8	28.7	30.5	92.7	30.9	29.8	29.3
					95.1			
24	91.0	31.7	29.6	29.7	93.3	31.1	30.4	29.5
					94.9			
25	91.8	32.3	30.8	28.7	93.3	31.1	30.9	29.8
					94.2			
26	92.7	31.4	31.7	29.6	93.6	31.2	31.1	30.4
					91.2			
27	93.5	30.4	32.3	30.8	94.5	31.5	31.1	30.9
					93.3			
28	94.2	31.1	31.4	31.7	95.7	31.9	31.2	31.1
					96.6			
29	94.9	32.2	30.4	32.3	96.9	32.3	31.5	31.1

Tabulation-sheet C--Derivation of summation or mass distribution-graph in 4-hour periods for a 24-hour storm for Redbank Creek--Concluded

No. of 4-hour periods	24-hour storm accumulative per cent	See text for derivation of columns (3), (4), (5)			8-hour storm accumulative per cent	See text for derivation of columns (7), (8), (9)		
(1)	(2)	(3)	(4)	(5)	(8)	(7)	(8)	(9)
					99.0			
30	95.5	33.0	31.1	31.4	97.2	32.4	31.9	31.2
					100.5			
31	96.1	33.5	32.2	30.4	96.9	32.3	32.3	31.5
					97.8			
32	96.7	32.6	33.0	31.1	97.2	32.4	32.4	31.9
					94.5			
33	97.2	31.5	33.5	32.2	97.8	32.6	32.3	32.3
					96.3			
34	97.7	32.1	32.6	33.0	98.7	32.9	32.4	32.4
					99.0			
35	98.0	33.0	31.5	33.5	99.3	33.1	32.6	32.6
					101.4			
36	98.5	38.0	32.1	32.6	99.6	33.2	32.9	32.9
					103.2			
37	98.9	34.4	33.0	31.5	99.6	33.2	33.1	33.1
					99.9			
38	99.2	33.3	33.8	32.1	99.3	33.1	33.2	33.2
					96.3			
39	99.5	32.1	34.4	33.0	99.6	33.2	33.2	33.2
					97.5			
40	99.6	32.5	33.3	33.8	100.0	33.3-1/3	33.1	33.1
41	99.7		32.1	34.4		33.3-1/3	33.2	33.2
42	99.8		32.5	33.3		33.3-1/3	33.3-1/3	33.1
43	99.9			32.1		33.3-1/3	33.3-1/3	33.2
44	100.0			32.5		33.3-1/3	33.3-1/3	33.3-1/3

based on similarity of topographic and physiographic features as are available from inspection of United States Geological Survey quadrangle-sheets. Generally, such transpositions were to adjacent or near-by streams of similar areas, shapes, and channel-slopes.

Attention is directed to the fact that the coefficients for lag used in this study were derived from unit-graphs with eight-hour distribution-percentages and based on eight-hour storms.

Initial approximations for obtaining distribution-graphs on unrated drainage-areas--(a) The S-curves shown in Figure 2 are applicable to areas under 2,000 square miles with conditions of topography and soil such as to produce relatively rapid runoff. In these cases the equation expressing the relationship between lag and the base of the unit-graph is as follows: $8y = (3x - 9.5)$, where x is the base in days and y is the lag in days.

(b) Entering Figure 2 with the lag of the unrated area known, trial distribution-graph percentages are selected. The S-curves reflect the physiographic characteristics inherent in the watershed in that the lag-character was determined by using a coefficient to represent variations in channel-slopes, land-slopes, stream-density, shape of watershed, stream-length, and other factors. The lag for the synthetic graph should be computed using values shown in Figure 1 as a guide. Distribution-percentages may then be obtained, using this value, from the S-curve in Figure 2. These percentages, set off in eight-hour intervals, multiplied by the volume of one inch of runoff over the watershed in day-second-feet, will give the unit-hydrograph in block form. The peak of the unit-graph may also be determined from the S-curve applicable to the determined lag in the following manner. For an eight-hour unit-storm, with eight-hour distribution-intervals, the peak is approximately equal to the drainage-area times 26.889 times 24 day-second-feet times maximum one-hour percentage of the S-curve. The peak-flow per square mile of drainage-area is then determined. Although the instantaneous peak-flow can be very accurately computed by

Tabulation-sheet D--Sample computation of check on mass distribution-graphs for a drainage-area of 125 square miles and a 6-hour lag

[1-inch runoff = 10,090 (1/3 day-sec-ft)]

No. of 8-hour periods	Accumulative per cent	Per cent in interval	First unit storm discharge in 1/3 day-sec-ft	Second unit storm	Third unit storm	Sum (4)+(5)+(6)	Column (7) repeated					Sum (7) to (12)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	19.4	19.4	1,960			1,960						1,960
2	64.7	45.3	4,570	1,960		6,530						6,530
3	78.5	13.8	1,400	4,570	1,960	7,930						7,930
4	85.7	7.2	730	1,400	4,570	6,700	1,960					8,660
5	90.6	4.9	490	730	1,400	2,620	6,530					9,150
6	93.7	3.1	310	490	730	1,530	7,930					9,460
7	95.9	2.2	220	310	490	1,020	6,700	1,960				9,680
8	97.5	1.6	160	220	310	690	2,620	6,530				9,840
9	98.7	1.2	120	160	220	500	1,530	7,930				9,960
10	99.4	0.7	70	120	160	350	1,020	6,700	1,960			10,030
11	99.9	0.5	50	70	120	240	690	2,620	6,530			10,080
12	100.0	0.1	10	50	70	130	500	1,530	7,930			10,090
13		100.0	10,090	10	50	60	350	1,020	6,700	1,960		10,090
14					10	10	240	690	2,620	6,530		10,090
15							130	500	1,530	7,930		10,090
16							60	350	1,020	6,700	1,960	10,090
17							10	240	690	2,620	6,530	10,090
18								130	500	1,530	7,930	10,090
19								60	350	1,020	6,700	8,130
20								10	240	690	2,620	3,560
21									130	500	1,530	2,160
22									60	350	1,020	1,430
23									10	240	690	940
24										130	500	630
25										60	350	410
26										10	240	250
27											130	130
28											60	60
29											10	10

This column has the discharge-values for the unit-storm combined three times.

this method, the construction of the S-curves does not justify its full acceptance. It is used, therefore, only as a guide in further determinations.

Final approximations--The natural summation-curves which are most nearly represented by the S-curves in Figure 2 had maximum percentages indicating peak-flows varying between 15 and 50 cfs per square mile and represent flows from the most typical basins in this District. If the peak-flow per square mile as obtained in the above computation is within these limits the distribution-percentages and base-length should be acceptable. If, however, the peak-runoff is computed to be 15 cfs per square mile or less, and the drainage-area under consideration has low, marshy areas and a flat channel-slope on the main stream, the runoff will be slower than for the average areas and an addition in base-length of the distribution-graph must be made. Conversely, where the peak-runoff per square mile is indicated to be over 50 cfs, as in the case of relatively impervious soils lacking forest-cover and with steep main and tributary channel-slopes, the runoff is terminated in less time than average and the base of the graph must be shortened.

If the base-lengths are altered, the entire summation-curve is not applicable and an arbitrary adjustment must be made. The following method is thought to give a fair approximation of true conditions. For actual unit-graphs having peak-runoff values less than 15 cfs per square mile the base-length appears to be 36 hours longer and for graphs having values greater than 50 cfs per square mile, about 18 hours shorter than those indicated by the S-curves.

In Figure 2 a line showing time of crest-occurrence (lag + 4 hours) has been drawn through the S-curves. Since lag is the primary computed element in the distribution-graph determination, it may be used as a fixed point for any subsequent changes.

Table 1--Drainage-basin characteristics for areas with discharge-records

Index No.	Name of stream and location of discharge-gage	Area square miles at gage	Ratio of width to length of area	Stream-pattern branches	Length of stream	Length to center of area	Snyder's C_t	Snyder's C_p	Peak per square mile of drainage-area	Peak of unit-hydrograph cfs	"Lag," hours	Base of graph, days
1	Allegheny R. above Kinzua, Pa.	2,190	0.34	1	102.5	48.0	2.19	0.363	8.3	18,100	28	10.3
2	Allegheny R., Kinzua to Warren, Pa.	954	0.30	2	56.5	32.5	2.74	0.32	11.3	10,800	18	6.7
3	Brokenstraw at Youngsville, Pa.	305	0.40	2	32.0	16.0	2.61	0.415	15.6	4,750	17	5.4
4	Oil Cr. at Rouseville, Pa.	300	0.46	2	36.0	19.5	1.54	0.45	26.2	7,850	11	4.4
5	French Cr. at Utica, Pa.	1,028	0.26	2	94.8	41.0	3.52	0.475	7.4	7,600	41	10.0
6	French Cr. at Saegerstown, Pa.	629	0.20	1	66.8	31.5	3.20	0.555	11.5	7,200	31	8.7
7	Sugar Cr. at Sugar Creek, Pa.	166	0.50	3	20.0	10.5	2.01	0.395	25.3	4,200	10	4.4
8	Tionesta Cr. at dam	483	0.42	1	47.0	19.0	2.21	0.52	19.6	9,450	17	6.4
9	Clarion R. at Clarion, Pa.	907	0.42	1	71.0	46.5	1.41	0.57	20.8	18,800	16	8.7
10	Redbank Cr. at dam	460	0.36	3	50.5	27.0	1.84	0.688	27.6	12,700	16	6.7
11	Mahoning Cr. at dam	341	0.42	2	38.5	20.0	2.73	0.527	16.9	5,750	20	7.4
12	Crooked Cr. at dam	278	0.34	2	43.0	26.0	1.34	0.482	28.0	7,780	11	4.4
13	Kiskiminitas above Vandergrift, Pa.	1,825	0.43	2	98.5	50.5	1.64	0.572	17.4	31,800	21	7.0
14	Conemaugh R. above Bow, Pa.	1,351	0.45	2	87.2	39.5	1.91	0.45	26.1	32,700	20	6.0
15	Loyalhanna Cr. at dam	291	0.30	1	42.6	21.5	2.40	1.23	46.3	13,450	17	3.7
16	.....	.....	....	...	.....	....	....	.....	....	.....	..	....
17	Turtle Cr. at East Pittsburgh, Pa.	146	0.67	2	17.6	7.2	1.18	0.355	44.8	6,550	5	2.7
18	Youghiogheny R. at Sutersville, Pa.	1,718	0.40	2	96.0	37.5	1.29	0.56	23.9	41,100	15	5.4
19	Youghiogheny R. at dam	435	0.40	1	40.1	25.8	1.66	0.482	22.0	9,580	14	6.7
20	Casselman R. at Markleton, Pa.	382	0.50	1	50.4	21.0	1.47	0.628	33.5	12,800	12	4.7
21	Laurel Hill Cr. at Ursina, Pa.	124	0.31	2	32.5	17.0	1.23	0.472	37.7	4,600	8	4.0
22	S. Fork of Ten Mile Cr. at Jefferson, Pa.	180	0.46	2	20.4	8.2	1.30	0.356	38.1	6,850	6	4.0
23	Dunkard Cr. at Bobtown, Pa.	230	0.30	1	34.8	16.0	2.24	0.693	29.6	6,800	15	4.0
24	Buffalo Cr. at Barrackville, W. Va.	115	0.60	2	22.4	12.2	1.67	0.572	40.7	4,680	9	3.0
25	Cheat R. at Beaver Hole, W. Va.	1,363	0.38	2	123.0	60.0	1.18	0.595	22.4	30,500	17	6.7
26	Cheat R. at Rowlesburg, W. Va.	972	0.43	3	40.0	24.0	2.04	0.473	19.0	18,400	16	5.7
27	W. Fork R. at Enterprise, W. Va.	750	0.50	3	75.5	35.0	1.07	0.37	21.5	16,100	11	6.0
28	Tygart R. at dam	1,184	0.20	3	108.0	55.0	1.55	0.474	14.4	17,100	21	11.4
29	.....	.....	....	...	.....	....	....	.....	....	.....	..	....
30	Chartiers Cr. at Carnegie, Pa.	260	0.30	1	33.0	17.5	2.68	0.689	24.5	6,400	18	5.7
31	Little Beaver R. at E. Liverpool, O.	505	0.58	2	43.0	17.0	1.38	0.347	22.3	11,250	10	5.4
32	Yellow Cr. at Hammondsville, O.	169	0.33	1	22.0	9.5	2.61	0.657	31.8	5,380	13	5.0
33	Raccoon Cr. at Moffatt's Mills, Pa.	178	0.32	1	35.5	19.0	1.71	0.538	28.7	5,100	12	5.0

Note: All computations made with slide-rule.

The basic equation, $8y = (3x - 9.5)$, states the relationship between lag and base for those flows applicable to the S-curves. If the base-flow correction is applied to this equation, a new lag will be determined. However, lag is a primary computed element in the distribution-graph development by this method and must be used in any subsequent changes. This can be accomplished by setting the zero time-point--an amount equal to (lag + 4 hours)--before the point of peak-occurrence and recomputing eight-hour percentages using this new starting time.

Studies made on the relationship between the peaks per square mile of drainage-area and the base of the unit-graph for the rated areas listed in Table 1 indicate that the following equation best fitted the skew-data: $q_p = KB^{-1.61}$, where q_p = peak in cfs per square mile of drainage-area, B = base of unit-graph in days, K = a constant which varies with the width-to-length ratio of the watershed and the flashiness of a stream, as reflected by the initially determined peak per square mile from the S-curves. With the selected base of the unit-graph the peak is then more closely approximated from the above formula with the aid of the parametric curves shown in Figure 3. The peak, base, and volume of the unit-hydrograph are known, while the time to crest equals (lag + 8 hours/2). The elements of the unit-hydrograph are now known and the unit-graph is now sketched in and minor adjustments to fit the required volume are then made. After this revision the ratio of the successive volumes in each interval to the total volume will give more accurate distribution-graph percentages for each eight-hour interval (or any other interval desired).

Conclusions--The chief aim of this paper is to add to the knowledge of synthetic unit-graphs. Mr. McCarthy's data were best suited to New England streams; Mr. Snyder's data were best suited in the Tennessee River Basin. The S-curves shown in Figure 2 are most suitable for the watersheds in the Pittsburgh Engineer District. It is expected that refinements in the curves shown in Figure 2 are warranted (1) as soon as more and more unrated streams have discharge-gages installed on them, (2) as soon as readings of gage-heights during rises become more frequent and possibly continuous, (3) as soon as the rating curves on many streams are revised to include more points at the higher stages of the rating curve, and (4) as soon as more exact methods of segregating surface-flow from runoff are determined.

The United States Geological Survey and Weather Bureau are cosponsors of a Work Projects Administration project in which it is aimed to compile physiographic characteristics of watersheds relating to the intensity of flood-flow. Some of the factors being determined are stream-pattern and density, slope of channel (principal and tributary), and slope of the land-surfaces. These data are still being developed and when ready it is the authors' intention to show what relation, if any, exists between each of the above-mentioned topographic indices (including also shape of a watershed) to the elements of its unit-hydrograph (peak, time to crest, base). Tentative results on such data at hand indicate no definite individual relationship, although it is believed that a combination of all the above-mentioned physiographic characteristics of a watershed can be made to determine more accurately the coefficient for lag, etc.

Acknowledgment is made of the cooperation of H. M. Hay and of the work of A. W. Wigdor, who assisted in the preparation of the Figures and computations for the tabulations. The present study is being made in the Projects Section, headed by E. P. Schuleen. All work in the Pittsburgh Engineer District is under the direction of Lt.-Col. W. E. R. Covell.

References

[1] G. T. McCarthy, The unit hydrograph and flood routing, U. S. Eng. Office, Providence, Rhode Island.

[2] F. F. Snyder, Synthetic unit graphs, Trans. Amer. Geophys. Union, 1938, pp. 447-454.

Addenda--Since the preparation of this paper, the attention of the authors has been directed to the existence of unpublished papers and reports which apply a graphical basic check on the unit-graph comparable to the distribution-graph computation shown in Table D. The employment of an S-curve in this paper applies to the distribution-graph for a unit-storm and not for the summation of a series of unit-hydrographs.

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NEW CURVE-FITTING METHOD FOR ANALYSIS OF FLOOD-RECORDS

John C. Geyer

The new curve-fitting technique described provides a direct and simple method for statistical analysis of the upper portion of the true frequency-series of flood-rises on any stream. The method is based only on the assumption that if the frequency-behavior of floods follows some uniform law it should be possible to express this law mathematically. Since a curve drawn by eye is sufficiently accurate for determining magnitudes whose frequencies are less than the length of the record, the primary reason for deriving a mathematical expression of behavior is to enable extrapolation of the curve in order to determine the magnitude of very infrequent floods.

The method developed meets certain important fundamental requirements. First, the series of observations used for analysis includes all the floods above an arbitrarily selected base-magnitude. That is, the partial frequency-series is used. Second, the results are independent of the base-magnitude above which floods are taken, provided only that the base is low enough to give a sufficient number of floods to describe the frequency-behavior. Third, an upper limiting flood-magnitude, which must be presumed to exist, is indicated. And finally, the method is fairly simple and may be applied rapidly to records for all types of streams.

R. E. Horton has developed a mathematical expression and curve-fitting method that accomplishes these ends. Although the two methods are fundamentally the same, both the technique and the resulting expression are different. Mr. Horton's method is described in Water-Supply Paper 771, "Floods in the United States."

Development of method--The mathematical expression found to describe the frequency of floods is

$$Y = LR^{-t^k} \tag{1}$$

where Y = flood-magnitude in sec-ft that has an exceedance-interval of (t), t = exceedance-interval in years, or is the average interval between floods which exceed (Y) in magnitude. It is the number of years in the record divided by the number of floods that exceed (Y). L, R, and k are constants for any stream. L = limiting magnitude (sec-ft), that is, Y = L when t = infinity; as explained with k below. R = ratio of the limiting flood to the flood with an exceedance-interval of one year, that is, R = (L/Y) when t = 1. k = constant which defines the curvature of the frequency-plot for any set of values of R and L. As the value of k is always negative, when t = infinity, $t^{-k} = (1/\infty^k) = 0$; the zero-power of R is one, therefore when $t = \infty$, Y = L.

The derivation of the formula for the San Gabriel River is used to describe the method for evaluating the constants, L, R, and k for any stream. However, the process will first be shown to be mathematically valid. Writing the logarithm of Y, equation (1)

$$\log Y = \log L - t^k \log R \tag{2}$$

and transposing

$$(\log L - \log Y) = t^k \log R \tag{3}$$

Taking logs again

$$\log (\log L - \log Y) = k \log t + \log \log R \tag{4}$$

This is a straight line when log (log L - log Y) is plotted against (log t), for if y = log (log L - log Y), x = log t, and b = log log R, equation (5) becomes y = kx + b, which is the slope-intercept form of the straight-line equation.

However, L is unknown and must be discovered by trial. This can be done very rapidly by the graphical method shown in Figure 1. Description of the procedure follows. On log paper plot log Y against t. [Actually log (Y/400) has been plotted for reasons explained later.] This plot gives the smoothed-in curve A (Fig. 1). Assume a value for log L and subtract the values of log Y along the curve A to obtain curve C. The curve C is then a plot of (log L - log Y) against t. Since log paper is used, this is equivalent to a plot of log (log L - log Y) against log t, which should produce a straight line if log L is properly chosen.

If log L is taken too high, a curve (B of Fig. 1) which is concave upwards will be produced. If log L is chosen too low a curve (D of Fig. 1) concave downwards results. A correct choice of log L produces the straight line C from which the constants R and k can be determined.

The log R appears at intersection of curve C with the ordinate t = 1. The constant k is the slope of the curve C and may be determined from the intersections of curve C with t = 1 and t = 100 as follows:

$$k = [\log (\log L - \log Y)_{100} - \log \log R]/(\log 100 - \log 1) \qquad (5)$$

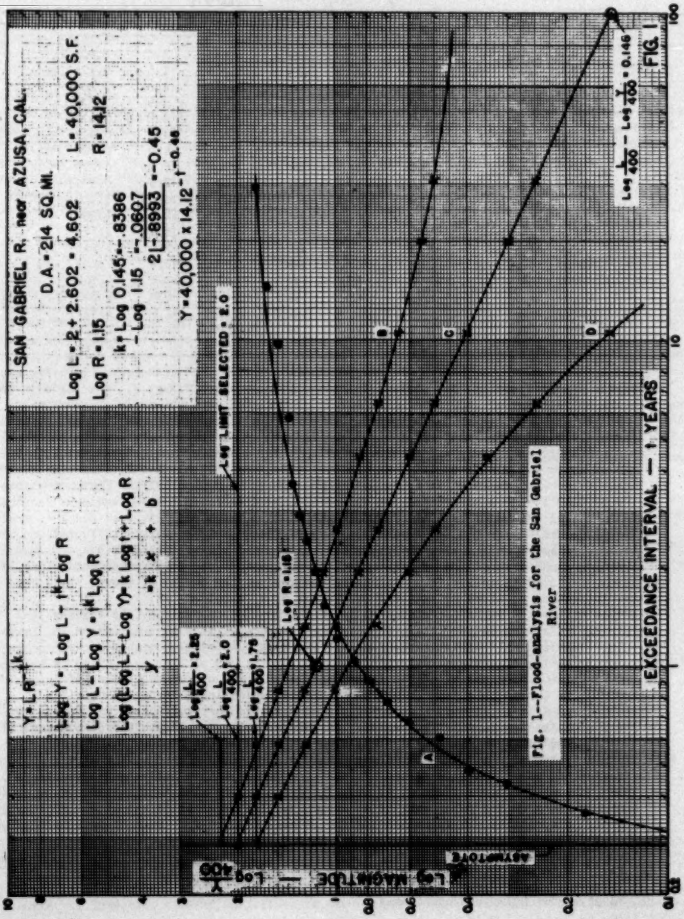
SAN GABRIEL R. near AZUSA, CAL.
D.A. = 214 SQ. MI.
L = 40,000 S.F.
R = 14.12
Log L = 2.+ 2.602 = 4.602
Log R = 1.15
k = Log 0.145 = .8386
- Log 1.15 = .0607
2 = .8993 = -0.45
Y = 40,000 x 14.12^-t^-0.45
Log Limit selected = 2.0
Y = L R^-kt
Log Y = Log L - kt Log R
Log L = Log Y + kt Log R
Log L = Log Y + k Log t + Log R
y = k x + b
EXCEEDANCE INTERVAL — t YEARS
Log Magnitude — Log X/200
Asymptote
FIG. 1

Fig. 1.--Flood-analysis for the San Gabriel River

Table 1--Analysis of floods on San Gabriel River near Azusa, California (drainage-area is 214 square miles, base is 400 sec-ft, record is for 29 years)

Group-bounds Y, sec-ft	Count of floods	Frequency in groups f	No. exceeding each group-bound	Exceedance-interval t, years	(Y/400)	log (Y/400)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
400	𝍸 𝍸 𝍸 𝍸	20	102	0.284	1.0	0.000
600	𝍸 𝍸 𝍸	15	82	0.354	1.5	0.176
800	𝍸 11	7	67	0.432	2.0	0.301
1000	𝍸 𝍸 1	11	60	0.474	2.5	0.398
1200	𝍸 1	6	49	0.605	3.0	0.477
1600	𝍸 1	6	43	0.675	4.0	0.602
2000	𝍸	5	37	0.785	5.0	0.699
2400	1111	4	32	0.906	6.0	0.778
3000	1111	4	28	1.04	7.5	0.875
4000	𝍸	5	24	1.21	10.0	1.000
5000	1111	4	19	1.53	12.5	1.097
5900	111	3	15	1.93	14.8	1.170
7000	11	2	12	2.42	17.5	1.243
8000	11	2	10	2.90	20.0	1.301
9000	111	3	8	3.62	22.5	1.352
10000	11	2	5	5.80	25.0	1.398
12500	1	1	3	9.67	31.2	1.494
16900	1	1	2	14.50	42.25	1.626
22300	1	1	1	29.00	55.7	1.746

Complete analysis for the San Gabriel is shown in Table 1 and Figure 1. The steps in the analysis are as follows:

(1) Prepare Table 1 [columns (1) to (7)]--

(a) Select convenient values of Y to be used for grouping the observed data. Y = 400 sec-ft is taken as the base-flood and the selected Y-values in sec-ft are shown in column (1).

(b) Tabulate from the record the number of observed floods between succeeding values of Y. This flood-count is shown in column (2).

(c) Column (3) is the numerical frequency of floods between values of Y, for example, there were 20 floods between 400 and 600 in magnitude.

(d) Beginning at bottom of column (3) the frequencies are accumulated and listed in column (4). Column (4) thus gives the number of floods which equalled or exceeded each value of Y in column (1).

(e) Divide the years of record (29 years for the San Gabriel) by the figures in column (4) to obtain the average exceedance-intervals, t, listed in column (5). This is the simplest and most conservative method of computing exceedance-intervals.

(f) Column (6) gives values of Y [column (1)] divided by the base-value of Y, or 400 in this case. This conversion is necessary in order to obtain as wide a range of (log Y)-values as possible for plotting on a fixed-scale log paper. For example, if values of log Y were plotted directly, the range in values would be: log 400 = 2.6 to log 22,300 = 4.3. The values 2.6 and 4.3 plot a vertical distance apart of one inch on the log paper used. However, if logs (Y/400) are plotted, the range becomes log 1 = 0 to log 55.7 = 1.746. The log 1 = 0 locates an asymptote because on log paper zero is at infinity. The vertical spread of all the other points is increased to five inches.

(g) Column (7) lists the values of log (Y/400).

(2) Plot log (Y/400) of column (7) against t of column (5) on log paper (see curve A, Fig. 1); 16- by 11-inch, 2 by 3 cycle log paper serves very satisfactorily for analysis of all types of streams.

(3) Draw the smoothed curve A.

(4) Subtract the values along curve A from assumed values of log (L/400) to obtain lines B, C, and D. The correct value of log (L/400) is 2.00 because this value produces the straight line C.

(5) If log (L/400) = 2, log L = (2 + log 400) = 4.602 and L = 40,000 sec-ft.

(6) At t = 1, log R = 1.15; therefore, R = 14.12.

(7) From equation (5), k = (log 0.145 - log 1.15)/(log 100 - log 1) = (-0.8336 - 0.0607)/2 = - 0.45.

Therefore the formula for the San Gabriel is $Y = 40{,}000 \times 14.12 \cdot t^{-0.45}$

The observed frequencies for the San Gabriel River are plotted in Figure 2, and the derived curve is superimposed to show goodness of fit. The circled dots are plotted points for the 29-year record of peak 24-hour (calendar day) floods published in United States Geological Survey Water-Supply Paper 771. In order to determine the effect of the 1938-flood upon the plotted frequencies, the data for the four years October, 1934, to September, 1938, were added to the record and frequencies were recalculated. The recalculated points are plotted as crosses. Below 9,000 sec-ft the extension of the record had very little effect upon computed frequencies. The curve derived from the 29-year record certainly fits the data for the 33-year record equally as well in this case. The analysis indicates that for the San Gabriel River, floods with frequencies ranging up from 100 years rapidly approach a limiting magnitude.

The peak-flows on the San Gabriel River for the two greatest floods, those of January 18, 1916, and of March 3, 1938, were 1.8 and 3 times the calendar-day floods. The limiting calendar-day flood indicated is around 40,000 sec-ft; therefore, it might be roughly estimated that the limiting peak-flood indicated is some 2.5 times the calendar-day limit, or is 100,000 sec-ft. This value, which amounts to approximately 500 sec-ft per square mile on a drainage-area of 214 square miles, is reasonable for the very flashy San Gabriel River.

Unfortunately, long and accurate records of peak-discharges on American streams are non-existent. The analyses must therefore be confined to study of the calendar-day maximums selected according to some arbitrary rule. The data for the San Gabriel River and for other streams discussed later, have all been taken from United States Geological Survey Water-Supply Paper 771. The arbitrary rule in that report was to select as an independent maximum value, each peak calendar-day along the continuous hydrograph which was ten per cent greater than adjoining depressions. The base-values were arbitrarily selected to give three to five times as many observations as there were years in the record. Many of the older figures for calendar-day discharges were calculated from only one or two gage-height readings and, therefore, are of questionable accuracy. In order to compare any figures for calendar-day values discussed subsequently with peaks estimated by other methods, it is necessary to study the ratio of calendar day to peak for the particular stream.

Analysis of other records--In Figures 2 and 3 are shown the curves for ten additional streams. Although these streams range widely in area and in flood-producing characteristics, the method described produces a curve which fits the observed values at all frequencies. The Tennessee River and the Juniata River are especially selected exceptions. Data for all of these streams and the values of the constants for the fitted curves are given in Table 2.

Of some 65 streams studied, only about ten do not have frequency-distributions that are well described by the equation used here. The deviation from normal is always in the higher floods which are greater than indicated by the frequency-trend of the lower magnitudes. This deviation may be due to chance occurrence of great floods in a short record or to inaccuracies in the estimated magnitudes of the greatest floods. However, in some rivers the frequency-behavior seems to follow consistently an entirely different curve above a certain magnitude, this indicating, as is often contended, that great floods occur on some streams much more frequently than is evidenced by the general frequency-behavior of ordinary floods. The records for the Juniata River at Newport, Pennsylvania, and the Tennessee River at Florence, Alabama, show this characteristic.

There is a sharp break in the plotted points for the Juniata River at about 80,000 sec-ft. As a matter of interest, a curve was fitted to the points above this value. This curve, shown as a dotted line in Figure 2, has been made to approach about the same limit as the solid curve

for the lower points, that is, 485,000 sec-ft. The fit is very good even though a predetermined limit has been imposed on the upper portion. It is impossible to say whether this unusual behavior has any significance until all doubt as to the accuracy of the recorded values for the higher discharges has been removed. The observed frequencies for both portions of the Juniata River curve fall so nearly in a straight line that any upper limit which is high enough will

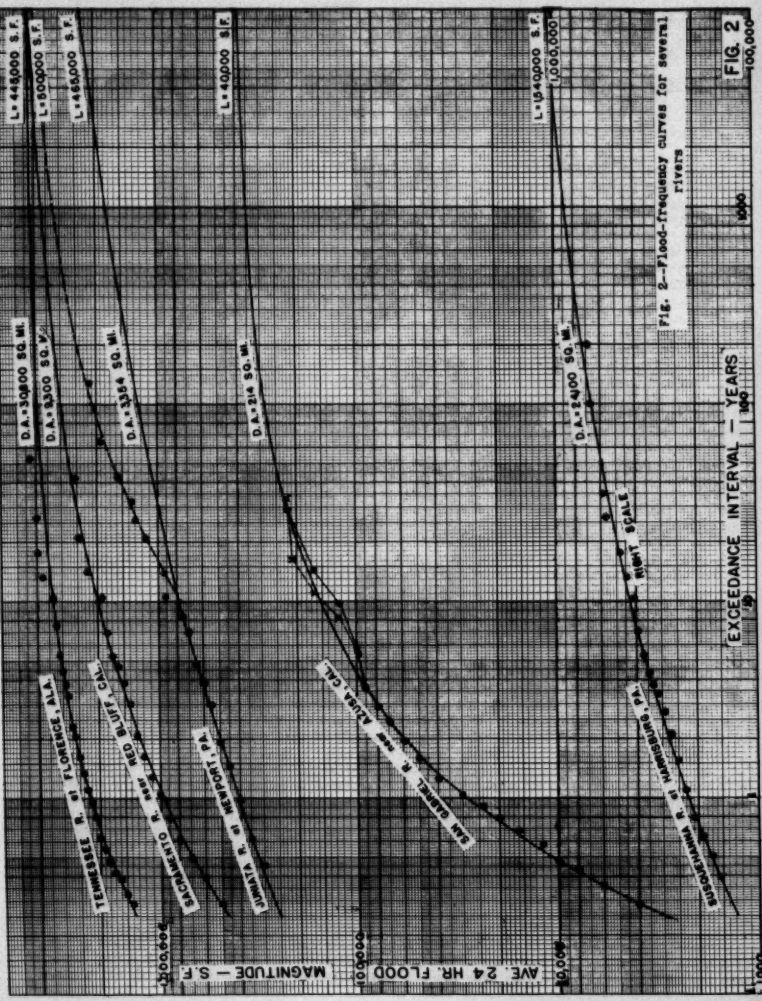

Fig. 2--Flood-frequency curves for several rivers

FIG. 2

give a curve that fits well. The limit selected in this case was the lowest one which would produce a curve that follows the points below 80,000 sec-ft.

The four highest observations for the Tennessee River at Florence, Alabama, are all between 10 to 15 per cent above the curve that gives best fit. It may or may not be significant that

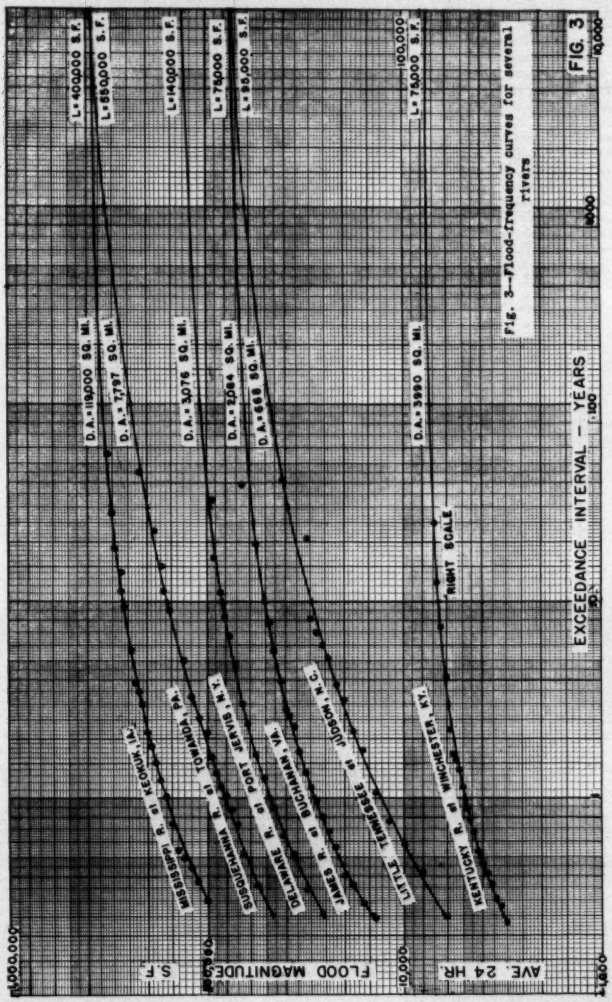

Table 2--Summary of data on the analysis of various flood-records*

Name of stream	Drainage-area, sq mi	Mean annual runoff		Years of record	No. of obs.	Annual 24-hour flood		Max. 24-hour flood in the record		Estimated max. limit 24-hour floods = (L)		Constant	
		sec-ft	sec-ft per sq mi			sec-ft	sec-ft per sq mi	sec-ft	sec-ft per sq mi	sec-ft	sec-ft per sq mi	R	K
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
San Gabriel R. near Azusa, Cal....	214	154	0.72	29	102	2,830	13.2	22,300	104	40,000	187	14.1	0.45
Little Tennessee R. at Judson, N.C.....	660	1,808	2.74	41	169	13,200	20.0	40,800	62	95,000	143	7.25	0.23
James R. at Buchanan, Va.....	2,084	2,540	1.22	39	161	28,800	13.8	66,700	32	75,000	36	2.63	0.376
Delaware R. at Port Jervis, N.Y...	3,076	5,541	1.80	33	122	48,000	15.6	93,100	30	136,500	45	2.85	0.333
Juniata R. at Newburg, Pa.....	3,354	4,466	1.33	{42 128}	92	40,000	12.0	213,000	64	465,000	138	{11.75[a] 63.1 0.354[b]}	0.133
Kentucky R. near Winchester, Ky.....	3,990	5,040	1.27	25	103	48,600	12.2	68,500	17	75,300	19	1.55	0.505
Susquehanna R. at Towanda, Pa.....	7,797	10,090	1.30	45	126	81,300	10.4	220,000	28	550,000	70	6.76	0.186
Sacramento R. near Red Bluff, Cal.....	9,300	11,340	1.22	42	145	95,300	10.2	254,000	27	500,000	54	5.25	0.258
Susquehanna R. at Harrisburg, Pa.....	24,100	34,740	1.44	{64 105 200}	162	222,000	9.21	691,000	29	1,540,000	64	6.92	0.186
Tennessee R. at Florence, Ala.....	30,800	52,040	1.69	53	186	222,000	7.2	430,000	14	445,000	14.4	2.00	0.385
Mississippi R. at Keokuk, Ia.....	119,000	60,600	0.51	56	186	161,000	1.35	314,000	2.6	400,000	3.4	2.47	0.35

*Data from Floods in the United States [U.S. Geol. Sur. W.-S. Paper No. 771].

[a]Portion of curve below 80,000 sec-ft.

[b]Portion of curve above 80,000 sec-ft.

these four floods were above the upper magnitude for which the gage-discharge relationship has been well determined.

The analysis of the Susquehanna River at Harrisburg, Pennsylvania, is presented for three reasons. First, this River is another example of one whose frequency-plot shows only slight curvature. The fitted curve with a limit of 1,540,000 sec-ft has been judged to follow the points best. However, the limit in this case can be lowered to around 1,200,000 sec-ft before the resulting curve obviously is a worse fit than that selected. Second, the limit for this stream has been checked by the unit-hydrograph method. Mr. Stegmaier, a graduate student at The Johns Hopkins University, working independently, estimated the limiting peak-flood on the Susquehanna at Harrisburg to be 1,600,000 sec-ft. This was on the basis of an assumed average of 11 inches rain and four inches water-content of snow over the 24,100-square mile drainage-area, all coming off in four days at 100 per cent runoff. The third reason for including the Susquehanna River is to illustrate how a long fragmentary record can be used when applying this method. It is known that the floods of 1889 and of 1936 were the largest that have occurred at Harrisburg during the last 200 years. Therefore the exceedance-intervals for these two magnitudes have been based upon a 200-year length of record. Moreover, the ten largest floods occurring in the last 105 years are also known, so the exceedance-intervals for these are based upon 105 years. The plot for the Susquehanna is thus a composite plot computed from 64-, 105-, and 200-year records. This procedure is very important since it lengthens the record for the portion of the curve where observed frequencies are apt to be most unreliable. Table 3 gives a comparison of results obtained by various other frequency-methods when applied to the Harrisburg record.

Table 3--Predicted floods on Susquehanna River at Harrisburg (drainage-area 24,100 square miles)--Comparison of methods

Frequency, years	Geometric frequency	Hazen, Foster III	Foster I	Slade	Author
(1)	(2)	(3)	(4)	(5)	(6)
2	262,000	251,000	255,000	250,000	280,000
10	404,000	428,000	437,000	425,000	435,000
20	458,000	506,000	520,000	500,000	506,000
50	526,000	610,000	620,000	620,000	601,000
100	584,000	683,000	685,000	686,000	673,000
200	672,000	767,000	750,000	755,000	743,000
500	695,000	855,000	815,000	845,000	832,000
1,000	745,000	936,000	862,000	910,000	895,000
10,000	930,000	1,190,000	985,000	1,080,000	1,080,000
100,000	1,110,000	1,440,000	1,060,000	1,200,000	1,222,000
1,000,000	1,310,000	1,690,000	1,120,000	1,300,000	1,324,000
10,000,000	1,510,000	1,950,000	1,170,000	1,360,000	1,400,000
100,000,000	1,740,000	2,200,000	1,220,000	1,410,000	1,445,000
∞	∞	∞	?	1,560,000[a]	1,540,000

[a] Limit used with Slade method is assumed on basis of other studies.

The curves in Figure 3 illustrate the results obtained by application of the foregoing method to a wide variety of streams which show what might be called normal-frequency distribution.

Summary of important features of the analysis--The important features of the semi-graphical method for analyzing the partial frequency series may be summarized as follows:

(1) The true flood-frequency is used for analysis.

(2) By making use of all significant information, the number of observations which describe the behavior is increased from three to five times the number used when annual floods only are analyzed.

(3) Historical data may be used to increase materially the effective length of record for the higher magnitudes.

(4) The mathematical expression has the proper limit-characteristics.

(5) The formula describes the frequency-behavior of all types of streams in terms of three constants (L, R, and k) and thus provides a means of comparing the flood-frequency characteristics of various streams.

(6) In most cases a reasonable upper limit is indicated by application of the method.

(7) The fact that the equation used is not based on theoretical considerations of probability might be considered by some to be a disadvantage. However, when skew-factors or normalizing functions are introduced into probability-analyses, the laws of pure chance are discarded and the statistical method becomes little more than curve-fitting as a means of extrapolation. It is believed that a direct approach to the problem of curve-fitting is more reasonable than attempts to determine a more-or-less complicated function of the variable which will behave according to the laws of pure chance. In the present method no impression is given that the laws of pure chance are involved. Neither is there a fallacious sense of accuracy which might accompany complex mathematical computations.

(8) The method is relatively simple and rapid of application. It is sufficiently flexible that judgment and results from other methods of approach can be utilized in determining the desired frequency-curve.

(9) Finally, the analysis should prove to be a valuable additional tool which may be used with the many other available techniques to guide the engineer toward safe yet reasonable estimates of the frequency and magnitude of future floods.

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RECENT MOVEMENTS OF NORTH ATLANTIC ICE AND A PROPOSED COAST GUARD EXPEDITION TO THE WEST GREENLAND GLACIERS

Edward H. Smith

In September, 1939, at the International Assembly just subsequent to the termination of the iceberg-season of 1939, a paper was given on icebergs, and their drift into the North Atlantic. The Coast Guard cutter Chelan, which I commanded, drifted with the last iceberg in the North Atlantic steamship-lanes, and witnessed its complete disintegration, then no longer a danger to shipping, on August 23, 1939.

It so happens that as this is being written, the first Arctic ice of the crop of 1940 has just been sighted. On April 3, 1940, in latitude 48° 40' north, longitude 50° 10' west, a steamship sighted strings of pack-ice--the vanguard of the procession which is now drifting southward with the wind and current. The United States Coast Guard since the middle of March has kept two cutters in readiness at Boston, Massachusetts, expecting under normal conditions that the first of the Arctic ice would put in an appearance off the Grand Banks about the first of March. This year, therefore, the ice is a month or more late and to date no icebergs have appeared. This is in marked contrast to last year when an area of pack-ice as extensive as New England covered the ocean off Newfoundland and many icebergs were drifting in the Labrador Current. There is a high correlation between pack-ice and icebergs. During 1939 there were 850 bergs that drifted south of Newfoundland. It ranked as a heavy ice-year along with 1909, 1912, 1929, and 1935, when 1024, 1019, 1351, and 875 bergs, respectively, were recorded. On the other hand, 1902, 1924, and 1931 produced only 41, 11, and 13 bergs, respectively. Such wide variations, although partially explained by variations in meteorological conditions in the northwestern North Atlantic and Arctic, do not tell the whole story.

It is only through the above type of long-range record (compiled by the United States Coast Guard) that little-suspected large-scale fluctuations of ice in the polar regions are detected. Similar marked changes have been recently observed as a result of the drift of the Russian icebreaker George Sedov as described in a paper by Professor Zubov of Moscow.

On July 26, 1937, the ice-breaker Sedov left the port of Murmansk on an expedition to the high latitudes of the Arctic. Having completed its scientific work along the Northern Sea Route, it sailed to the New Siberian Islands, where it met the ice-breakers Sadko and Malygin. All three vessels became icebound close to one another as the Laptev Sea became frozen in.

The ice-breakers began to drift with the ice in a northeasterly direction on October 23, 1937. The joint drift continued for ten months. During that time they covered 2,600 km, charting a tortuous line on the map of the central Arctic Basin, first to the northeast and then to the northwest. An air-expedition and the ice-breaker Yermak were sent in April, 1938, to the assistance of the drifting vessels. Three flights were made by the airmen, who removed 184 persons to the mainland.

When the Yermak succeeded in battering its way through the ice to the three vessels in August, 1938, it could only escort the Malygin and the Sadko to open water. The steering gear of the Sedov had been damaged by the ice and the vessel had to be left. Coal, clothing, and

food for four years, including live hogs, spare radio-apparatus, scientific equipment, and other material were left with the Sedov. If the vessel was to remain in the ice, its drift might as well be used for scientific purposes. The Sedov was therefore transformed into a scientific station. This was the beginning of the second part of the drift of the Sedov in the Arctic ice, which lasted 16 more months. Disaster hung over the vessel and its men on many occasions during this time. Every movement of the ice threatened to crush the vessel or to hole it and send it to the bottom.

During the drift of the Sedov of over two years she was carried across the central Polar Basin to the Greenland Sea, passing much closer to the Pole than did the Fram, or any other vessel. On more than one occasion the Sedov was subjected to severe pressures as the polar cap-ice was jammed together under the effects of strong winds and gales. The Fram, it will be recalled, was especially designed by Nansen and a Norwegian shipwright, with a wedge-shaped cross-section, causing the hull to rise under the effects of ice-pressures thus slipping out of a nip instead of being crushed in. It is all the more remarkable that the Sedov, not possessing this construction, survived this journey--the first instance of such a beset vessel returning from the deeper parts of the central Polar Basin.

The J. Stalin, flagship of the Soviet Arctic Fleet, left Murmansk on December 15, 1939, to go to the assistance of the Sedov and to release her as she was now approaching the margin of the Arctic pack. When within 100 miles of the icebound-vessel, the Stalin found its way blocked by a solid barrier of ice and had to return for fuel. Leaving Barentsburg on January 1, 1940, the Stalin again met bad weather as it battled northward through the heavy ice. The two vessels were about 20 miles apart on January 3, 1940, when the Sedov reported having seen the other's searchlight. On January 6 the Stalin was five miles away, having taken nearly two days to cover the previous 15 miles. A halt was then called pending the formation of cracks in the solid ice-field around the Sedov. The two vessels finally met on January 13, and the 26-month Arctic drift of the Sedov was over.

Observations in glaciology, meteorology, oceanography, and terrestrial magnetism were carried out continuously throughout the period of over two years. Reports were made by radio to the Union of Soviet Socialist Republics so that in case of disaster to the Expedition, no loss of records would result. The fact that during a part of this period the Russians were also manning the North Pole Station and also obtaining observations from a second beset ice-breaker (the Lenin) in the southwestern part of the Laptev Sea, all contributes to make the scientific data more nearly complete. The fact also that the drift of the Sedov crossed that of the Fram permits direct comparison between the two vessels' observations, although they are separated in time by 45 years.

Some of the early findings compared with those of the Fram and preliminary data indicate:

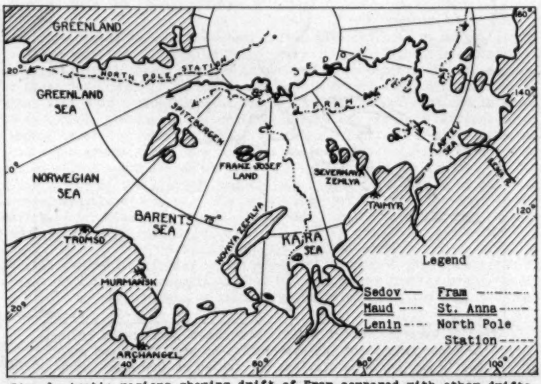


Fig. 1--Arctic regions showing drift of Fram compared with other drifts

(1) The depth of the Polar Basin is greater than had heretofore been assumed.
(2) Early-reported land north of the New Siberian Islands is non-existent.
(3) The discharge of the ice from Arctic Basin into the Greenland Sea according to the drift of the Sedov is much accelerated over what formerly existed. The westward drift that required 25 months in the Fram was covered in 16 months by the Sedov.
(4) Warmer water and a decrease in the thickness of the Polar cap-ice was observed.
(5) All three Russian stations reported the presence of the intermediate warm-water layer found by Nansen but with its temperature considerably higher.
(6) The winter monthly mean air-temperatures north of the 83rd parallel over a considerable period recorded consistently higher than those reported by Nansen.
(7) The drift of the ice-fields in the central Polar Basin amounted to one-fiftieth of the velocity of the wind.
(8) The drift of the ice in the open Arctic Ocean parallels the isobars and is proportional to the barometric radient.
(9) Theoretical drifts of the North Pole Station, Sedov, and Lenin plotted on the above assumptions were astonishingly close to the actual drifts.
(10) The velocity of the current discharging into the Greenland Sea is weak at the Pole; less than one km a day. As the Greenland Sea is approached the current increases from four km at the 83rd parallel to nine km at the 75th parallel.

The observations on the behavior of the heavy Polar cap-ice is all the more significant inasmuch as the Sedov's drift lay through a region where permanent ocean-currents are either weak or completely absent and far from the distorting influence of land. Practical laboratory-

Fig. 2--Proposed United States Coast Guard post-season cruises in oceanography and ice-observation to west Greenland and Baffin Bay [program provides for census of icebergs during each of the next three summers]

conditions prevailed, therefore, for studying the wind-effects on the movement of the ice over a relatively long period.

As a result of the studies which the scientists of the Union of Soviet Socialist Republics have been engaged upon for the past several years, they now feel that the Arctic is undergoing a change to a warmer climate. They point out that the general volume of ice in the seas bordering the Soviet Arctic is on the whole steadily diminishing. It is claimed that as a result of the decrease of the iciness of these seas vessels are penetrating further and further northward. The retreat of the southern edge of the Polar pack-ice has led to the appearance of fish in regions where earlier they were altogether absent. All this gives the Soviet Government considerable encouragement of an eventual opening up of the North Sea Route to commerce and assuring a direct passage to the Orient.

According to this view-point the increase of warmth is not confined to the Russian sector but embraces the Barents and Kara seas as well. The average air-temperature is stated to be rising everywhere in Europe with the rivers freezing later and breaking up earlier. The past severe winter in Europe is claimed to have been only an interruption in this general trend. The foregoing conclusions are supported by more observations from a larger number of Arctic stations than has ever been obtained before and consequently constitutes more substantial proof and evidence than would otherwise be the case.

Even the average winter air-temperatures around the shores of Baffin Bay and Greenland are claimed to have risen. This may have been one of the causes of the previously reported large numbers of icebergs during the past two years off Newfoundland. A gradually warming climate for the Greenland Region may have permitted more of the sea-ice to break away and drift southward with the abnormally large number of icebergs. There seems to be a consistency in this particular view inasmuch as visitors to the iceberg-glacier front along the west coast of Greenland during 1937 and 1938 sighted enormous numbers of icebergs drifting seaward in the currents. The summer of 1939, on the other hand, northern waters were noticeably bare as if the region had been entirely evacuated of glacier-ice.

The last three years have witnessed wider variations in the amount of pack-ice and icebergs in the western North Atlantic Ocean than is normal. Early indications of the winter and spring of 1940 point to as light an ice-season this year as 1938 and 1939 were heavy. The fact that little ice was observed in Baffin Bay last summer agrees well with the scarcity of ice this spring (the bulk of last year's crop normally appearing south of Newfoundland this spring).

An Advisory Board recommended to the United States Coast Guard last autumn, following the 1939 outburst of ice, that in view of the unusual Arctic ice-conditions reported in west Greenland, ice-observation cruises to the west coast of Greenland and Baffin Bay should be undertaken by the Ice Patrol during each of the next three summers. It is hoped that observations near the sources of the bergs will furnish information of practical value in furtherance of protection which the International Ice Patrol affords shipping in the North Atlantic.

If, however, a cruise to west Greenland waters materializes, it may be divided into two parts; the oceanographic vessel General Greene reoccupying a line of stations between southern Labrador and Cape Farewell, Greenland. Upon her return it has been proposed that one of the lake-type of Coast Guard cutters be fueled and depart from Sydney, Cape Breton, to accomplish an ice-observation cruise of approximately 4,000 miles. No fuel or supplies in bulk can be obtained north of Sydney. In case a cutter is available and the international situation permits, the vessel should proceed directly northward to Disko Bay, visiting the southernmost one of the iceberg-glaciers (Jackoshavn) and then continue northward (ice-conditions being favorable), making a circuit of Melville Bay as far as Cape York. The number and general distribution of the icebergs in the offing of the glaciers and the extent and distribution of pack-ice in Baffin Bay will be the chief objects of record. The return trip should skirt the edge of the west ice, along the Baffin Land and Labrador Coast. The entire cruise should occupy about two weeks provided good weather is experienced.

If this ice-observation program is followed, it is trusted that considerable interesting information will be collected, especially when it is combined for the Arctic as a whole. It is hoped that a report on the progress of this work can be given at the next meeting of the American Geophysical Union.

U. S. Coast Guard,
Washington, D. C.

THE DISTRIBUTION OF THE AVERAGE DEPTH OF SNOW ON GROUND IN NEW YORK AND NEW ENGLAND (II): CURVES OF AVERAGE DEPTH AND VARIABILITY

Robert G. Stone

The aims and general methods of this study as begun in 1936 under the auspices of the National Park Service and continued by the Blue Hill Observatory, were described and illustrated by examples in a previous communication to this Section [see 1 under "References" at end of paper]. Some further examples of the maps and diagrams which have been made were presented at the Meeting of the International Commission of Snow in Washington in September, 1939 [2]. Similar studies of snow-cover have since been made for Wisconsin by E. R. Miller [3] and for Washington by P. E. Church [4].

The present paper gives the results of one phase of the study which forms a convenient unit of general interest from hydrologic, climatological, ecological, and commercial points of view, namely, the curves of average depth-of-snow cover from beginning to end of the snow-season. The average depths were computed for the 15th day and end of every month having any snow, for each of about 230 stations, for as many years up to 1936 as were on record in the manuscript files of the United States Weather Bureau. None of this material has ever been published by the Bureau or any other agency. Isarithmic snow-depth maps were made from these averages and these will be published elsewhere. However, because the maps involve considerable smoothing, interpolation, and other sources of judgment and possible error, it is important to publish the actual data for the computed averages, both in graphical and tabular form. It is hoped that eventually the tables of the individual twice-monthly depths year by year can also be published or mimeographed, as they will be of great value for more particular analyses by engineers, foresters, and climatologists. We are able only to point out the features evident in our curves, without any systematic analysis of their physical causes.

Practically all of the records over five years' length have been plotted. Records shorter than ten years do not usually give reliable averages, but in most cases the records between five and ten years' length are sufficiently approximate to the normal to be given practical consideration in a study such as we have been making. Table 1 shows the results of computing successive overlapping three- and five-year means in a long snow-depth record. The differences between these successive means gives one a good idea of the reliability of a short record in northern New England and in most of New York. Places with lighter snowfall, as along the Atlantic coast, show greater variability, so that longer records are necessary for a reliable average there than in snowier parts of the region. We have also computed the standard deviations for a few stations (Table 2), which lead us to the same conclusion as did the successive three- and five-year means--that is, the variability is greater in the less snowy localities, which in our region means the more southerly parts, the Atlantic and part of the Great Lakes littoral. Likewise the beginning and end of the snow-season show greater variability than the mid-season. (Owing to the varying skewness in the frequency-distributions of snow-depths, these standard deviations are not strictly comparable measures of dispersion.)

The plotted curves for our 230 stations, when viewed together, are somewhat confusing in their many and often striking differences of form. As a first approximation to an ordered classification of these curves we have drawn them parallel and close together in groups, in which each curve is apparently of similar type (Figs. 1-5). Each type is defined not merely by homology of shape but also by its relation to a more or less distinct continuous physiographic region or climatic region. It must be recognized that mere similarity of form does not necessarily mean similarity of physical causes. However, a similar constellation of physiographic and meteorologic factors can recur in far separated areas, and therefore any final decisions as to the physical or causal bases of apparent similarities in the curves of stations separated by considerable distances are very dubious unless the similarity of the physical causes can be independently substantiated. Within these limitations we believe our tentative classification reveals many real and consistent features of regional climatic character, that, while probably not in all cases of practical importance, suggest problems for research. The most immediate value of our classification of curves into regional types is that it often permits a fair estimation of the character of the snow-regime at points between the stations having records, and facilitates a quick bird's-eye view of the leading observed features of snow-cover variation with season and locale.

The process of classification was begun with mere sorting of curves by form, then by plotting the regions of each type on a map. A study of this map led to revision of the first classification and in turn to a new map, which is shown in Figure 6 for New York and Figures 7 and 8 for New England. The geographical arrangement is much simpler and more a priori understandable

Table 1--Snow on the ground at Bethlehem, New Hampshire *

Central season of aver.	October		November		December		January		February		March		April	
	15	End	15	End	15	End	15	End	15	End	15	End	15	End
(A) Three-year moving averages														
1894-95	0.0	0.0	1.8	3.0	6.0	3.7	4.7	9.0	17.5	12.0	10.7	4.0	0.0	0.0
1895-96	0.0	0.0	0.3	3.0	3.3	3.3	3.0	10.0	10.8	8.7	12.3	6.0	0.0	0.0
1896-97	0.0	0.0	1.3	0.0	3.0	4.7	3.7	13.0	13.1	14.0	13.3	3.3	0.0	0.0
1897-98	0.0	0.0	1.3	7.4	8.0	4.0	5.0	13.0	20.7	19.3	7.7	12.3	2.3	0.0
1898-99	0.0	0.0	2.7	7.3	6.7	4.7	6.3	15.0	21.0	21.0	15.0	16.3	5.0	0.0
1899-00	0.0	0.0	7.3	8.0	12.0	9.0	9.3	22.0	25.0	19.0	22.7	22.0	5.0	0.0
1900-01	0.0	0.0	12.7	4.3	7.0	9.3	11.0	14.3	17.3	17.7	20.3	12.7	2.7	0.0
1901-02	0.0	0.0	11.3	5.3	11.1	9.0	12.0	9.0	19.0	13.3	10.0	6.7	0.0	0.0
1902-03	0.0	0.0	5.3	5.0	7.3	5.0	12.0	9.0	14.0	7.7	11.3	0.7	0.0	0.0
1903-04	0.0	0.0	4.0	3.7	8.7	5.7	10.7	13.3	18.0	14.0	9.0	0.0	0.0	0.0
1904-05	0.0	0.0	4.0	2.7	7.3	6.3	9.0	11.3	19.3	13.3	10.8	0.3	0.0	0.0
1905-06	0.0	0.0	5.0	2.8	7.7	8.3	6.0	8.3	19.7	17.0	14.8	1.0	0.0	0.0
1906-07	0.0	0.7	1.0	0.7	5.0	5.3	6.7	4.0	11.7	10.3	7.1	1.0	0.0	0.0
1907-08	0.0	1.0	2.3	0.7	4.3	7.0	7.7	12.0	8.3	11.3	8.3	4.0	0.0	0.0
1908-09	0.0	1.0	1.3	2.7	3.7	7.0	10.3	12.0	8.3	5.0	4.7	3.3	0.0	0.0
1909-10	0.0	0.3	2.1	4.0	8.3	9.7	8.0	11.3	11.7	5.7	6.7	5.3	0.0	0.0
1910-11	0.0	0.0	3.0	4.0	6.3	6.5	10.3	9.7	15.7	12.0	8.7	4.0	0.0	0.0
1911-12	0.0	0.0	3.1	4.3	5.3	4.5	7.0	7.0	11.7	11.7	7.0	4.0	0.0	0.0
1912-13	0.0	0.0	2.3	1.5	1.7	4.1	9.3	9.0	15.0	12.0	8.7	6.0	0.0	0.0
1913-14	0.0	0.0	0.1	1.5	1.5	4.5	5.0	4.7	10.7	4.5	4.0	1.0	0.0	0.0
1914-15	0.0	0.0	0.0	0.5	6.1	5.8	6.0	3.7	12.0	5.5	14.0	2.3	0.0	0.0
1915-16	0.0	0.0	3.3	0.3	7.5	7.5	4.3	7.3	12.3	8.5	18.0	2.7	0.0	0.0
1916-17	0.0	0.0	3.3	1.0	14.7	11.3	12.3	15.0	17.7	11.3	22.7	3.0	0.0	0.0
1917-18	0.0	0.0	3.3	1.1	--	--	--	--	--	--	--	--	--	--
1918-19	0.0	0.0	0.0	1.1	--	--	--	--	--	--	--	--	--	--
1919-20	0.0	0.0	0.0	2.5	--	--	--	--	--	--	--	--	--	--
1920-21	0.0	0.0	3.8	6.7	5.7	6.1	10.1	14.7	28.0	27.7	--	--	--	--
1921-22	0.0	0.0	3.8	--	5.3	9.8	12.5	13.8	--	19.7	--	--	--	--
1922-23	0.0	0.0	3.8	--	4.0	10.3	9.1	9.7	--	15.0	--	--	--	--
1923-24	0.0	0.0	0.0	--	0.3	9.3	9.5	18.7	--	14.0	13.0	2.7	0.0	0.0
1924-25	0.0	0.0	0.0	2.0	0.3	4.3	6.0	12.0	7.7	12.3	14.7	6.7	4.0	0.0
1925-26	0.0	0.0	0.0	2.0	2.3	8.7	14.7	12.7	10.0	16.0	14.3	6.7	4.0	0.0
1926-27	0.0	0.0	0.0	0.0	2.3	7.0	14.0	7.7	12.0	15.0	13.0	6.7	4.0	0.0
1927-28	0.0	0.0	0.0	0.7	3.3	7.3	--	--	9.7	13.3	4.7	0.0	0.5	0.0
1928-29	0.0	0.0	0.0	1.0	2.3	4.3	--	--	9.7	7.0	3.3	0.0	0.5	0.0
1929-30	0.0	0.0	0.0	1.3	4.3	7.0	--	--	13.7	10.7	9.0	1.3	0.5	0.0
1930-31	0.0	0.0	0.0	0.7	3.0	6.7	5.0	9.7	11.7	6.7	11.3	3.0	0.0	0.0
1931-32	0.0	0.0	0.0	0.3	2.7	4.0	4.0	9.0	10.3	12.7	20.7	6.3	0.0	0.0
1932-33	0.0	0.0	0.7	0.0	1.7	6.0	5.7	9.0	12.7	19.7	21.3	8.3	0.0	0.0
1933-34	0.0	0.0	1.7	0.0	2.0	8.3	8.3	15.7	15.3	23.0	20.3	6.7	0.0	0.0
1934-35	0.0	0.0	1.7	0.0	2.7	10.0	10.3	22.0	22.9	30.0	13.3	3.3	0.0	0.0
1935-36	0.0	0.0	1.0	1.3	1.7	5.0	--	--	--	--	--	--	--	--
(B) Five-year moving averages														
1895-96	0.0	0.0	1.9	1.8	4.4	3.4	4.6	11.8	15.7	16.8	9.6	3.8	0.0	0.0
1896-97	0.0	0.0	0.6	6.2	6.0	5.8	4.4	10.6	17.3	14.4	10.2	9.8	1.4	0.0
1897-98	0.0	0.0	1.8	4.4	5.8	3.4	5.0	13.6	16.9	15.7	15.0	11.6	3.0	0.0
1898-99	0.0	0.0	5.2	4.8	8.0	6.6	7.0	15.6	20.2	21.0	16.8	14.6	3.0	0.0
1899-00	0.0	0.0	8.4	7.0	8.2	7.4	9.2	13.2	21.2	19.8	15.0	13.8	3.0	0.0
1900-01	0.0	0.0	7.5	7.6	10.8	7.6	10.0	11.6	19.8	13.4	13.7	11.6	3.0	0.0
1901-02	0.0	0.0	7.5	3.4	7.6	7.2	11.2	13.2	16.2	14.0	13.0	7.6	1.6	0.0
1902-03	0.0	0.0	9.2	4.8	9.4	8.0	11.8	12.2	19.6	15.6	11.4	11.4	0.0	0.0
1903-04	0.0	0.0	5.6	4.4	8.0	6.0	9.8	8.8	17.0	10.0	6.5	6.5	0.0	0.0
1904-05	0.0	0.0	5.0	2.5	8.0	6.6	8.2	9.6	17.6	13.6	9.7	9.7	0.0	0.0

* Readings at 6 p.m.

Table 2--Standard deviations of snow-depths

Item	October		November		December		January		February		March		April
	15	End	15	End	15	End	15	End	15	End	15	End	15
Bethlehem, N. H. (1893-1936)													
σ, inches	---	0.33	4.58	4.49	6.18	4.12	5.40	4.13	9.58	11.85	11.61	6.58	2.50
Av. depth, in.	0.0	0.0	2.0	2.7	4.6	6.6	8.6	11.8	15.4	14.7	12.9	4.8	0.8
σ, per cent	---	0.0	229	166	134	63	63	35	62	81	90	135	312
No. years	44	44	44	43	43	43	42	42	42	43	42	42	43
Colchester, Conn. (1893-1936)													
σ, inches	---	---	0.61	2.78	3.97	2.84	4.05	3.87	3.95	5.35	2.92	---	---
Av. depth, in.	0.0	T	0.1	0.6	1.7	1.8	1.5	3.0	4.0	2.9	0.8	T	T
σ, per cent	---	---	610	464	234	158	270	129	99	184	365	---	---
No. years	44	44	44	44	44	44	44	44	43	43	42	43	43
Auburn, N. Y. (1898-1936)													
σ, inches	---	1.00	1.747	1.491	2.650	2.221	2.967	3.290	2.641	2.755	3.158	---	---
Av. depth, in.	---	0.01	0.6	0.5	3.4	3.5	5.0	6.0	6.5	4.9	2.4	0.5	T
σ, per cent	---	10000	291	298	78	63	59	50	41	56	131	---	---
No. years	39	39	39	40	39	39	39	39	39	38	38	38	38
Enosberg Falls, Vt. (1904-1936)													
σ, inches	---	---	1.73	2.02	3.48	3.61	4.05	7.57	5.56	6.00	6.22	3.92	0.42
Av. depth, in.	0	T	0.8	1.3	3.4	5.2	6.1	8.0	9.2	8.3	5.4	1.5	0.1
σ, per cent	---	---	216	155	102	70	66	95	60	72	115	262	420
No. years	32	32	32	32	32	32	32	32	33	33	33	33	33

in New York than in New England, no doubt partly because of the more regular physiographic structure of New York State, but also because west-wind snowstorms are more characteristic in New York, while the northeasterly snowstorms more common in New England are less influenced by topography.

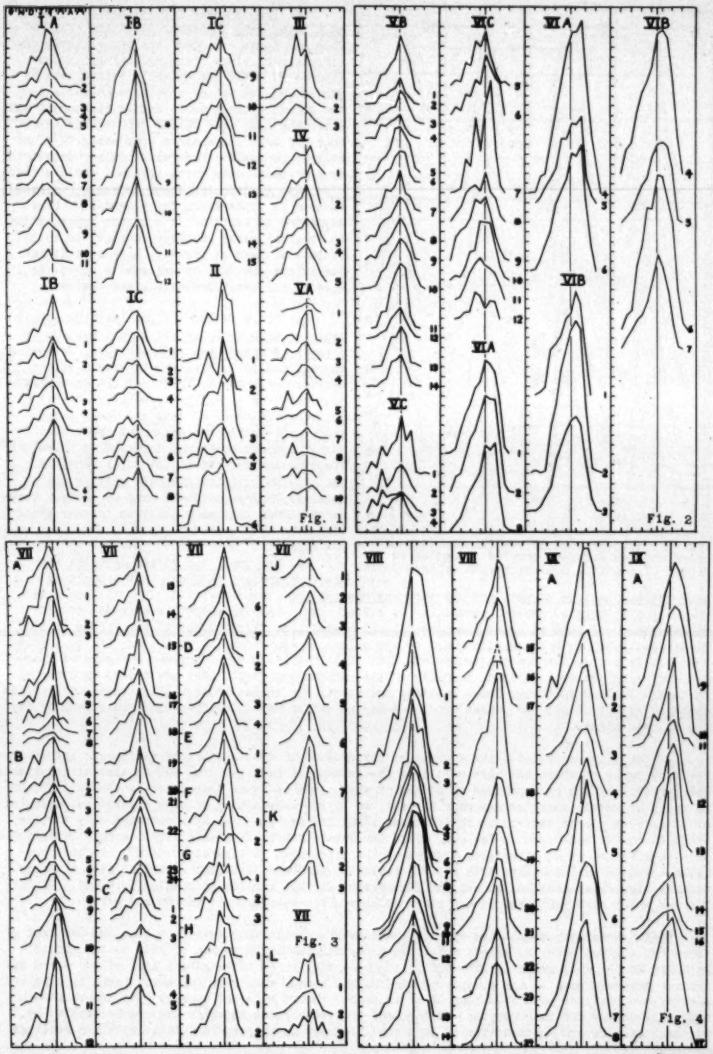
Table 3 gives a detailed synopsis of each curve-type--listing the stations and their elevations and lengths of record--and Table 4 gives the actual figures from which the curves are plotted. Suffice it to mention here that the date of the highest maximum and the general height of this maximum--that is, its "peakedness"--form the chief criteria for the classification, while the secondary maxima and minima serve to distinguish the sub-types. Within some major types there is a more or less steady gradation from one secondary feature to another, particularly in Type VII of New England. These gradations do not make satisfactory types from the geographical point of view where the gradations in form of curve do not take place in a sequence corresponding to some sequence of topographic situations. Even so they may still represent a real climatic sequence, but unfortunately we have no handy criterion for proving that these cases are anything more than a geometrical sequence without physical continuity.

In general, the distribution of types appears to be topographically controlled, but in drawing the boundaries between types we have perhaps exaggerated that fact by using it as a guide where the stations were too few. The topographic influence is evident enough in New York and western New England, nevertheless, to be accepted with some confidence.

As to the causes of many anomalous features characterizing some of the types, we can hazard some meteorological theories, but it is very risky to publish any but the most reasonable views for the most definite features. In this category we note the following:

(1) The early seasonal maxima and secondary maxima along the shore of Lake Erie and on the ridges or plains some distance back from the shore of Lake Ontario (types III, II, IV, IB, IC)--These are undoubtedly in part related to the instability snowstorms in cold-air masses that have first passed over the relatively warm and still unfrozen Lakes.

(2) The early and late maxima of the Atlantic coastal region in New York, Long Island, and Connecticut (types VA, VB, VIIA, VIIB, XII, VIIF)--These are known to result from the tendency for occasional very heavy snowstorms to develop from late fall and late winter tropical or subtropical cyclones that pass northeastward along the seaboard and in which the cold air just reaches far enough southeast to bring the surface-temperature below freezing while the warm air (with its high absolute humidity) is lifted above it vigorously. The intensity of these storms decreases into winter.



Figs. 1-4--Depth-of-snow curves for stations in New York and New England grouped according to type
(Unit of vertical scales is inch of snow-depth)

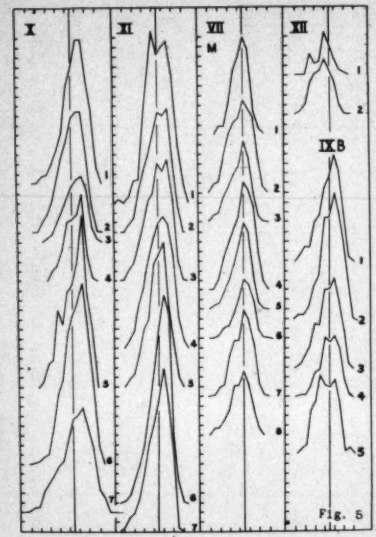


Fig. 5--Depth-of-snow curves for stations in New York and New England, grouped according to type (Unit of vertical scales is inch of snow-depth)

(3) The tendency for the maxima to occur at a later date at higher altitudes (Fig. 9)--This was to be expected from temperature-considerations, since freezing weather is continuous at these places until rather late in winter and the winter snowfalls accumulate on the ground without much loss by thaw until well after the time when vernal warming has begun. Once the mean temperature approaches 32°F the melting is rapid. The result is an asymmetric type of snow-cover curve (gradual early-winter rise, late maximum, and steep decrease in spring), as seen in types VIII, IX, X, and XI. (The asymmetry in certain other of the types is due to abnormal early secondary maxima due to influence of lake or ocean.) Note that at low elevations the date of maximum is about the same at all latitudes within the region.

(4) It is rather obvious that the actual depth of snow-cover at its annual maximum increases northward and with altitude, following thermal control. However, the ratio of the maximum depth to the length of the snow-season does not show a regular temperature-relation owing to influence of lake and ocean which tends to lengthen the season of snow-cover out of proportion to the duration of below-freezing weather and to the total snowfall. The station with the greatest maximum depth (Ashland, Maine) does not have any longer snow-cover season than many stations farther south with much less snow.

(5) The small but rather definite mid-winter temporary decrease that appears at some valley stations of northern New York and New England (types VIA, VIC, IXB, XI) could be due to one or more of several causes, or to all of them: (a) Tendency to recurrence of mid-winter thaws or rains at about the same date (± a week); or (b) tendency to recurrence of mid-winter anticyclonic weather with sunshine and a lack of snowstorms at that time; or (c) a snow-shadow effect from surrounding mountains. But it is difficult to understand how some of these tendencies can be so localized; possibly in the surrounding region they are masked by other factors. Yet the fact that these stations are nearly all in basins or valleys suggests that the combined effect of all the causes mentioned may be rather more localized than the effect of any one of them alone.

Variability--Admittedly the average of the snow-depth does not afford sufficient information for many purposes where the variability of the snow-cover from year to year is also of importance. The variability can be appraised in different ways, such as by an inspection of the full record of daily or weekly observations year by year, or by the computation of some statistical measures of dispersion of the individual observations about the average. We have computed only the few standard deviations given in Table 2, since the labor in this is prohibitive. A more satisfactory view is afforded by an expectancy diagram of the type shown in Figures 10 to 27. We have prepared these for all stations with records accurate, complete, and long enough to give a statistically significant result, as well as for several shorter records of special interest. Except for two which were published in our previous paper [1], they are all reproduced here.

These expectancy-graphs are of value because one can quickly read from them the per cent of years (at a given date) to expect more than a certain number of inches of snow on the ground. In order to prepare a graph of this sort, it is necessary first to compute a list of the seven-day average depths of snow on the ground for each winter week of each year for which there is a record available. Stations with less than 15 or 20 years' record will not usually give smooth enough frequency-curves for this purpose. The longer the record, the smoother the graphs tend to be. The next step in the construction of this kind of graph is to prepare a table with the headings as below.

Consecutive No. of week beginning with first week of October	No. of cases (upper figure) and percentage of all cases	Depth of snow in inches					
		0	>0	≥1	≥5	≥10	≥15
1	20	5	15	15	10	0	0
	100	25%	75%	75%	50%	0%	0%
2	20	0	20	20	18	2	0
	100	0%	100%	100%	90%	10%	0%

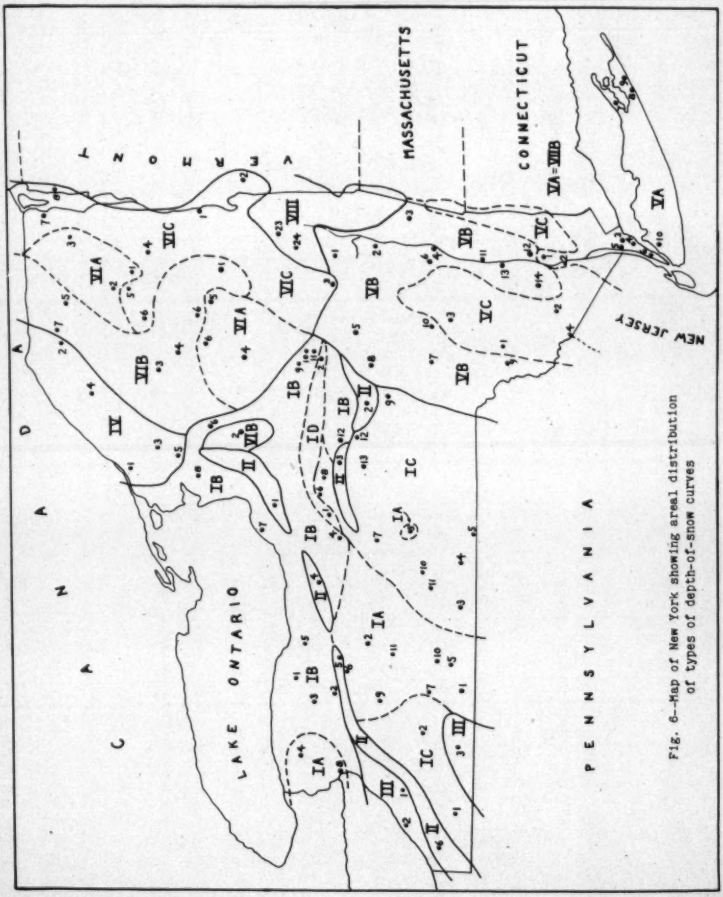


Fig. 6--Map of New York showing areal distribution of types of depth-of-snow curves

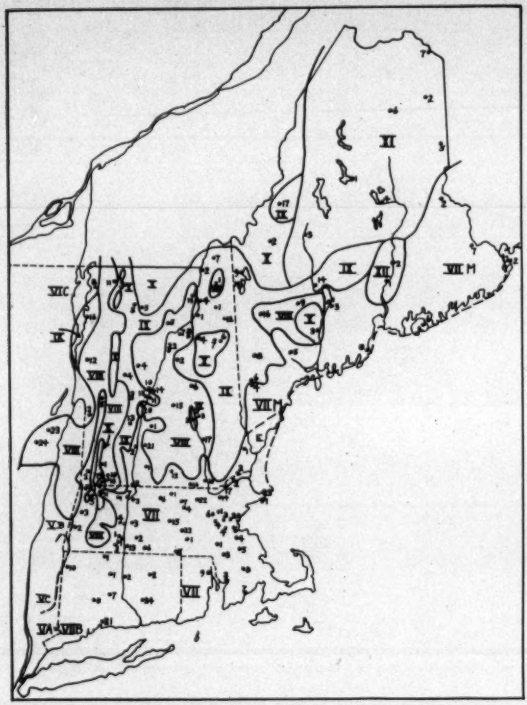


Fig. 7--Map of New England showing areal distribution of types of depth-of-snow curves

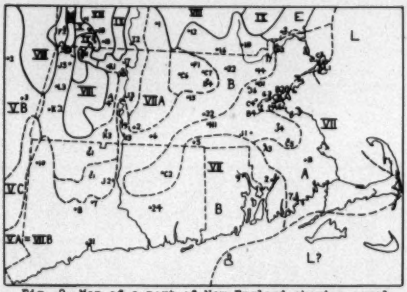


Fig. 8--Map of a part of New England showing areal distribution of types of depth-of-snow curves

Table 3--Key to stations on Figures 6, 7, and 8, and description of curve-types

No.	Place	Altitude feet	Years
	IA--Maximum end of January; sometimes secondary maximum middle of December (Western New York, interior)		
1	Bolivar	1800	14
2	Hemlock Lake	920	19
3	Ithaca	836	37
4	Lockport	520	26
5	Andover	1650	15
6	York	760	15
7	Angelica	1420	24
8	Buffalo	167	20
9	Letchworth Park	1260	24
10	Alfred	1840	17
11	Dansville	703	20
	IB--Maximum mid-February; often a secondary maximum in mid or end of December (Western New York, Lake Ontario littoral)		
1	Brockport	537	13
2	Stafford	910	6
3	Elba	750	4-12
4	Auburn	715	39
5	Rochester	523	45
6	Lowville	900	33
7	Oswego	335	45
8	Adams Center	680	22
9	Salisbury	1300	41
10	Dolgeville	685	17
11	Little Falls No. 1	890	40
12	Morrisville	1325	24
	IC--Maximum mid-February; prominent secondary maximum or equal maximum in mid-January with lesser secondary maxima in mid-December (Western New York, interior, back from the Lake littoral)		
1	Jamestown	1390	30
2	Franklinville	1600	19
3	Addison	1000	26
4	Elmira	863	23
5	Waverly	824	16
6	Syracuse	599	35
7	King Ferry	392	15
8	Fayetteville	530	17
9	New Lisbon	1234	22
10	Perry City	1038	15
11	Wedgewood	1350	22
12	Bouckville	1420	16
13	De Ruyter	1365	21
	ID--Maximum between end of January and mid-February (Mohawk-Genessee Basin from Little Falls to Skaneateles)		
1	Skaneateles	875	19
2	Little Falls No. 2	375	16
	II--Mid-February chief maximum with important secondary, sometimes equal maximum, at the end of or mid-December (ridges, scarps, and uplands parallel to but somewhat inland from shores of Lakes Ontario and Erie)		
1	Palermo	460	15
2	Edmeston	1200	5
3	Cazenovia	1200	6
4	Lyons	426	7
5	Avon	585	9
	III--Mid-January maximum (southwest corner of State of New York, near Lake Erie)		
1	Perrysburg	1500	9
2	Fredonia	765	23
3	Allegheny	1345	22
	IV--End or middle of February maximum, marked secondary at mid or late December (St. Lawrence valley, Northern New York)		
1	Alexandria Bay	283	5
2	Lawrenceville	462	6
3	Philadelphia	485	28
4	Canton, N.Y.	448	30
5	Watertown (near)	497	32
	VA--Maximum in middle or late February; prominent secondary maximum in December at some stations (Long Island and lower Hudson valley, New York)		
1	West Point	386	26
2	Glenham	170	5
3	Scarsdale	50	33
4	Mt. Vernon	155	22
5	Mt. Hope	200	20
6	New York City (Battery Park)	5	45
7	Cutchogue, L. I.	32	38
8	Southampton, L. I.	36	18
9	Bridgehampton, L. I.	60	7
10	Flushing, L. I.	60	21
	VB--Maximum in mid-February; secondary maximum at some stations in mid or late December or mid-January (middle Hudson valley and Western Catskills, lower Mohawk and Schoharie basins)		
1	Ballston Lake	300	26
2	Albany	97	45
3	Chatham	470	17
4	Athens	90	17
5	Sharon Springs	821	24
6	Cairo	340	13
7	Delhi	1460	12
8	Cooperstown	1200	40
9	Jeffersonville	1240	34
10	Roxbury, N.Y.	1490	21
11	Rhinebeck	215	10
12	Wappingers Falls	150	32
13	Rifton	190	15
14	Walden	400	15

Table 3--Key to stations on Figures 6, 7, and 8, and description of curve-types--Continued

No.	Place	Altitude feet	Years
	VC--Maximum in mid-February; secondary maxima prominent at mid-December and mid-November (Catskill Mountains and lower Wallkill valley, New York)		
1	Liberty, N.Y.	2000	13
2	Middletown	700	8
3	Griffen Corners	2260	13
4	Port Jervis	550	38
	VIA--Double-peaked maximum, mid-February and mid-March (northern and western valleys and piedmont of the Adirondacks, New York)		
1	Lake Placid (transition, Feb. max. only)	1826	28
2	Gabriels	1750	29
3	Dannemora	1440	31
4	North Lake	1833	31
5	Indian Lake	1660	23
6	Raquette Lake	1775	22
	VIB--Single maximum, end or middle of February (northern and western valleys and piedmont of the Adirondacks; top of Tug-Hill Plateau, New York)		
1	North Creek	1014	8
2	High Market	1786	12
3	Wanakena	1500	8
4	Nehasane	1770	8
5	Chasm Falls	1100	10
6	Blue Mountain Lake	1750	10
7	Moira	420	30
	VIC--Double maximum, mid or late January and mid or late February, one or other maximum predominating (eastern and southern Adirondacks, and western Champlain basin, New York and Vermont)		
1	Ticonderoga, N.Y.	340	12
2	Wells, Vt.	900	23
3	Amsterdam, N.Y.	610	2-8
4	Keene Valley, N.Y.	1012	20
5	Saranac Lake, N.Y.	1620	11
6	Tupper Lake, N.Y.	1720	12
7	Chazy, N.Y.	200	5-8
8	St. Albans, Vt.	250	5-6
	VIIA--Maximum at end or mid-February, with secondary maximum at end of November (intermediate uplands of Central New England and southeast Massachusetts)		
1	Keene, N.H.	550	29
2	Ludlow Center, Mass.	239	8
3	Mansfield, Mass.	190	6 1/2
4	Leeds, Mass.	390	8
5	Rutland, Vt.	610	2-5
6	Roxbury, Mass.	107	8
7	New Bedford, Mass.	63	25
8	Middleboro, Mass.	53	23
	VIIB--Maximum at end or mid-February, with secondary maximum in middle of December; equivalent to type VA in New York State (Rhode Island, southern Connecticut, lower Connecticut River valley, sheltered interior low valleys in southern New England)		
1	Mt. Tom, Mass.	199	7
2	Somerset, Mass.	40	29
3	Williamstown, Mass.	711	41
4	Weston, Mass.	224	19
5	Webster, Mass.	450	9
6	Monson, Mass.	420	19
7	Southington, Conn.	140	27
8	Waterbury, Conn.	340	35
9	Providence, R.I. (station has data for end of each month only)	160	32
10	Cream Hill, Conn.	1300	39
11	Hoosac Tunnel, Mass.	800	6
12	Peterboro, N.H.	744	10
13	Springfield, Mass.	199	28
14	No. Billerica, Mass.	125	13
15	Rutland, Mass.	1160	15
16	Brookline, N.H.	250	14
17	Lawrence, Mass.	57	44
18	Nashua, N.H.	125	16
19	Holyoke, Mass.	90	15
20	Cambridge, Mass.	74	8
21	New Haven, Conn.	68	45
22	Worcester, Mass.	625	43
23	Groton, Mass.	325	16
24	Colchester, Conn.	460	44
	VIIC--Maximum at end or mid-February, with secondary maximum at end of December		
1	Canton, Conn.	900	30
2	Storrs, Conn.	640	20
3	Rockport, Mass.	25	33
4	Chestnut Hill Reservation, Mass.	124	8
5	Brockton, Mass.	110	27
6	E. Templeton, Mass.	1200	13
7	Fitchburg, Mass.	402	43
	VIID--Maximum at end or mid-February, with secondary maxima at middle of December and middle of January		
1	Bedford, Mass.	129	15
2	Haverhill, Mass.	50	43
3	Turners Falls, Mass.	200	21
4	Leominster, Mass.	540	33
	VIIE--Maximum at end of February, with secondary maximum between mid-December and mid-January (Atlantic littoral of New Hampshire)		
1	Durham, N.H.	83	30
2	Newton, N.H.	200	24

Table 3--Key to stations on Figures 6, 7, and 8, and description of curve-types--Continued

No.	Place	Altitude feet	Years
	VIIF--Maximum at end of February, with secondary maximum between end of December and middle of January; also secondary maximum at middle of November		
1	Ashburnham, Mass.	1008	5-8
2	Bennington, Vt.	840	9
	VIIG--Maximum at end of January and end of December, with secondary maximum at middle of December or end of December		
1	East Hartland, Conn.	1220	20
2	Bellows Falls, Vt.	280	7
3	Belmont, Mass.	39	4
	VIIH--Maximum at end of January, with secondary maximum at end of December		
1	Millbury, Mass.	330	7
	VII I--Maximum in mid-January to end of January, with weak secondary maximum at end of December (along Connecticut River in southern New Hampshire and Vermont)		
1	Newport, N.H.	790	7
2	Vernon, Vt.	228	22
	VIIJ--Maximum at middle of January, with no secondary peaks (Connecticut River terraces and interior Boston basin)		
1	Norfolk, Mass.	244	13
2	Hartford, Conn. (station has data only for end of each month, which accounts for smooth curve)	159	17
3	Amherst, Mass.	217	20
4	Blue Hill Observatory, Mass.	630	44
5	Adams, Mass.	750	6
6	Concord, Mass.	139	40
7	Greenfield, Mass.	165	7
	VIIK--Maximum between mid-January and end of January (foothills of western Massachusetts [Hoosac] upland)		
1	Shelburne Falls, Mass.	400	6
2	Stockbridge, Mass.	850	6 1/2
3	Westfield, Mass.	475	6
	VIIL--Maximum between end of January and end of February, with secondary maximum at end of December (outer littoral of Massachusetts and Maine)		
1	Gloucester, Mass.	15	6
2	Eastport, Me. (station has data for end of each month only; the true type of curve is therefore uncertain)		34
3	Pittsfield, Mass. (this station may belong to type VIC)	1037	16
	VIIM--Maximum in mid-January, with a weak secondary at middle of January (inner littoral of southern Maine)		
1	Fairfield, Me.	90	14
2	Danforth, Me.	386	20
3	Winslow, Me.	90	25
4	Cornish, Me.	370	28
5	Lewiston, Me.	182	31
6	Bar Harbor, Me.	20	25
7	Woodland, Me.	140	19
8	Belfast, Me.	165	16
	VIII--Maximum in mid-February or with tendency for maximum to spread towards the end of February; weak secondary minimum at end of November or mid-November (foothills and valleys of southern and western Vermont, east central New York and southern New Hampshire, and upper Connecticut valley)		
1	Somerset, Vt.	2080	22
2	Dixville Notch, N.H.	1650	6
3	Sanbornton, N.H.	830	11
4	Chelsea, Vt.	1070	28
5	St. Johnsbury, Vt.	711	43
6	Plymouth, N.H.	500	37
7	Littleton, N.H.	1400	16
8	Bethlehem, N.H.	1440	44
9	Farmington, Me.	425	44
10	Norwich, Vt.	1150	31
11	Enosburg Falls, Vt.	422	33
12	Cornwall, Vt.	504	27
13	Jacksonville, Vt.	1000	18
14	Hanover, N.H.	603	36
15	Grafton, N.H.	863	25
16	Rumford, Me.	505	37
17	Concord, N.H. (station has data for end of each month only; true type of curve is therefore uncertain)	350	39
18	Wilmington, Vt.	1640	4-5
19	Bloomfield, Vt.	930	27
20	Hartland, Vt.	665	9
21	Alstead, N.H.	1120	29
22	Woodsville, N.H.	450	10
23	Glens Falls, N.Y.	349	41
24	Mt. McGregor, N.Y.	1060	18
	IXA--Maximum in mid-February or end of February, with tendency to weak secondary maximum at end of January at some stations (valleys and intermediate uplands of eastern Vermont, eastern New Hampshire, and west central Maine)		
1	West Milan, N.H.	1016	3-5
2	Glencliff, N.H.	1650	18
3	Franklin, N.H.	390	16
4	Stratford, N.H.	1000	13
5	Whitingham, Vt.	1450	6
6	Hiram, Me.	375	7
7	Pittsburg, N.H.	1660	19

Table 3--Key to stations on Figures 6, 7, and 8, and description of curve-types--Concluded

No.	Place	Altitude feet	Years
	IXA--Continued		
8	No. Bridgton, Me.	450	43
9	Upper Dam, Me.	1484	10
10	Middledam, Me.	1430	10
11	West Lebanon, N.H.	340	5
12	Berlin, N.H.	1110	26
13	Cavendish, Vt.	800	29
14	Madison, Me.	257	18
15	White River Junction, Vt.	490	11-13
16	Burlington, Vt.	404	31
17	Jackman, Me.	1180	10
	IXB--Maximum at end of February, with prominent or equal maximum at mid or end of January		
1	Lancaster, N.H.	1100	6
2	West Stewartstown, N.H.	1050	7
3	Woodstock, Vt.	800	30
4	Rochester, Vt.	825	8
5	Hyde Park, Vt.	576	7
	X--Maximum at mid-February or end of February, with a secondary maximum at end of December at some stations (high mountains of central New England and valleys of Canadian border region of New England)		
1	Searsburg Mt., Vt.	2360	6-7
	X--Continued		
2	Eustis, Me.	450	26
3	Gardiner, Me.	139	24
4	Twin Mt., N.H.	1500	4
5	Garfield, Vt.	1300	2-9
6	Pinkham Notch, N.H.	2000	10
7	Mt. Washington, N.H.	6280	7
	XI--Double maximum end of January and (secondary) mid-March; or double-peaked maximum mid-March and (secondary) middle of February; or the end of January and mid-March maxima join, giving a single maximum at end of February (northern Maine)		
1	Ripogenus, Me.	965	11
2	Presque Isle, Me.	606	18
3	The Forks, Me.	570	17
4	Millinocket, Me.	388	34
5	Houlton, Me.	365	26
6	Ashland, Me.	650	11-12
7	Van Buren, Me.	510	14
	XII--Maximum at end of January, with secondary maximum in middle of December (lower Penobscot valley, Maine)		
1	Bangor, Me.	61	4
2	Old Town, Me.	108	16

The number assigned to each week refers to its order in the season beginning with October 1. The number of cases refers to the number of years for which there are records of the mean weekly snow-cover for that particular week. Next, list the number of cases in the first week with no inches of snow-cover in the first column marked 0 and on a line with the week marked 1. This is followed out for all the weeks of the winter, and for all the different depths of snow-cover. The next step is to determine the per cent each figure represents of the total number of cases for that week. The zero-inch line, the greater-than-one-inch line, etc., can then be plotted on a graph with the weeks on one axis, and the percentage on the other. On some of the diagrams we have plotted a 0-curve (dashed) as an inversion of the >0-curve, as a convenience to show the expectancy of no snow-cover in the same sense as that for given amounts of snow.

By using percentages, all dates and stations plotted in the diagrams can be readily compared in terms of the probable number of cases in 10 or 100 years. In the expectancy-graph for Lake Placid, for example, we find that on the 20th, 21st, and 22nd weeks after October 1, there is an expectancy of 100 per cent of having more than four but less than eight inches of snow-cover. This means that there is over four inches of snow on the ground in every year at these times of the season. This particular graph was based on the records of 17 to 20 years. If the data for one more year, as for the winter of 1936-37, had been included, the expectancy would have been changed only slightly, since the interval from 85 per cent to 100 per cent is equivalent to an expectancy of over eight out of ten years. Graphs of this sort are of value for winter-sports planning. If a resort owner wishes to know whether the snow will repay the investment over a given period of years, and assuming that ten weeks with ten inches or more of snow on ground per year is needed or desired for seven out of the next ten years, the probability of receiving that amount of snow-cover depth-duration can be read off from the expectancy-diagram in a moment.

The writer has been ably assisted by Miss S. Govern and J. H. Conover to whom he wishes to express his gratitude for their perseverance at the tedious statistical work and mapping. Dr. C. F. Brooks has given valuable criticisms. The standard deviations were computed by J. Levine.

Table 4--Average depths of snow-cover in inches at given dates

[° = stations for which we also have averages of seven daily readings centered on the 15th and end of each month, used in making the expectancy-diagrams; + = broken record with many gaps]

Station	Altitude, feet	Period	Total record, years	Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.	
				15	31	15	30	15	31	15	31	15	28-29	15	31	15	30
Adams, Mass.	750	1930-36	7	0.0	0.0	0.2	0.6	0.8	1.4	3.4	6.7	7.8	6.1	2.2	0.1	0.1	0.0
°Adams Center, N.Y.	680	1900-21	22	T	T	2.4	3.2	9.6	11.9	13.2	14.1	18.1	11.9	8.9	1.9	0.5	T
°Addison, N.Y.	1000	1898-23	26	0.0	0.0	T	T	1.7	1.8	3.7	3.4	4.2	2.1	1.1	0.2	T	0.0
Albany, N.Y.	97	1893-37	44	0.0	0.0	0.1	0.2	1.8	1.9	2.8	3.3	5.4	2.5	1.4	0.2	T	0.0
°Alexandria Bay, N.Y.	283	1932-36	5	0.0	T	0.8	0.6	1.8	2.9	4.5	4.0	4.0	5.9	2.4	1.2	T	0.0
°Alfred, N.Y.	1840	1920-36	17	0.0	T	0.4	0.8	1.7	2.7	5.3	6.4	5.4	4.6	2.2	0.4	T	0.0
Allegheny, N.Y.	1346	1907-18 1924-36	22	0.0	T	0.8	0.9	1.9	3.5	4.7	4.2	3.4	2.4	1.1	0.0	0.0	0.0
Alstead, N.H.	1120	1893-22	30	0.0	0.0	1.2	2.5	5.4	6.5	8.0	10.1	14.5	14.3	8.5	2.1	0.3	0.0
Amherst, Mass.	217	1893-36+	35	0.0	0.0	0.1	0.6	1.3	2.2	3.0	5.5	7.6	5.2	0.9	0.1	0.0	0.0
Amsterdam, N.Y.	610	1902-23+	8	0.0	T	0.2	0.8	6.9	5.4	15.4	8.6	18.6	23.0	9.0	1.6	T	0.0
°Andover, N.Y.	1650	1922-36	15	0.0	T	0.1	0.3	1.2	0.8	2.6	3.6	2.3	1.4	1.7	0.2	0.1	0.0
°Angelica, N.Y.	1420	1903-29+	24	T	T	0.3	0.1	1.0	6.2	4.2	5.1	4.0	2.2	0.9	0.3	T	T
Ashburnham, Mass.	1008	1906-29+	10	0.0	0.0	1.8	1.0	2.3	5.3	5.1	4.1	10.0	13.0	3.2	1.3	1.0	0.0
°Ashland, Maine	650	1911-22	12	0.0	0.4	1.6	4.7	8.1	12.3	19.4	27.7	36.9	42.9	39.0	13.0	4.4	0.5
°Athens, N.Y.	90	1901-17	17	0.0	0.0	0.1	T	2.8	2.6	3.4	4.0	5.0	2.3	0.8	0.2	T	0.0
°Auburn, N.Y.	715	1898-36	39	0.0	T	0.6	0.5	3.4	3.5	5.0	6.0	6.5	4.9	2.4	0.5	0.0	0.0
Avon, N.Y.	585	1899-10	10	0.0	0.2	0.4	0.4	4.1	2.9	2.6	3.4	3.0	0.9	2.0	T	0.0	0.0
Ballston Lake, N.Y.	300	1903-30+	26	0.0	0.0	0.4	0.7	3.9	4.3	6.2	7.3	12.2	9.4	6.7	1.2	0.0	0.0
Bangor, Maine	61	1926-36+	6	0.0	0.0	T	0.0	4.3	2.2	2.8	8.7	6.0	3.2	1.0	0.5	0.0	0.0
°Bar Harbor, Maine	20	1901-36+	27	0.0	0.0	0.1	0.7	2.1	2.6	5.2	8.2	12.1	11.1	7.8	1.9	0.3	0.1
Bedford, Mass.	129	1893-23+	15	0.0	0.0	0.0	0.3	2.2	3.2	3.5	6.6	9.2	8.2	1.5	0.5	0.0	0.0
Belfast, Maine	165	1887-04	18	0.0	0.0	1.4	1.6	3.2	5.2	10.1	10.3	13.1	10.3	5.4	1.6	0.0	0.0
Bellows Falls, Vt.	280	1930-36	7	0.0	0.0	0.0	0.1	1.7	3.0	3.5	7.6	5.5	7.3	0.6	0.4	0.6	0.0
Belmont, Mass.	39	1901-05	5	0.0	0.0	0.0	0.0	4.4	3.4	5.5	6.6	5.2	1.9	0.5	0.0	0.0	0.0
Bennington, Vt.	840	1896-33+	7	0.0	0.0	0.3	0.8	0.9	2.8	4.2	3.6	5.5	8.5	1.9	0.8	0.0	0.0
°Berlin, N.H.	1110	1896-04 1917-34	25	0.0	0.0	0.6	2.8	4.2	7.7	11.4	13.9	16.4	17.3	14.0	6.8	2.5	0.0
°Bethlehem, N.H.	1440	1893-36	44	0.0	0.0	2.0	2.7	4.6	6.6	8.6	11.8	15.4	14.7	12.9	4.8	0.8	0.0
Bloomfield, Vt.	930	1906-36+	29	0.0	0.1	1.6	1.4	4.1	8.0	10.4	13.3	17.4	17.0	12.7	5.5	1.2	0.5
Blue Hill Obs., Mass.	630	1895-38	44	0.0	T	T	0.5	1.5	2.2	3.2	4.4	6.9	4.7	2.2	0.2	T	0.0
Blue Mt. Lake, N.Y.	1750	1902-11	10	0.0	0.0	2.8	3.9	13.2	17.5	25.1	24.9	31.9	31.5	26.2	21.7	7.7	1.3
Bolivar, N.Y.	1800	1906-12	14	0.0	0.1	1.1	0.8	4.3	3.4	5.3	9.8	9.0	5.9	2.6	0.4	T	0.0
°Bouckville, N.Y.	1420	1900-15	16	0.0	T	0.9	1.1	4.5	5.9	7.7	7.6	10.9	9.4	7.1	1.2	0.2	T
Bridgehampton, N.Y.	60	1930-36	7	0.0	0.0	0.0	0.0	0.4	1.9	T	1.6	1.5	1.3	T	T	0.0	0.0
°Brockport, N.Y.	537	1900-12	13	0.0	0.0	0.3	0.6	3.3	2.7	5.2	6.5	10.4	7.0	2.7	0.3	0.1	T
Brockton, Mass.	110	1896-36+	27	0.0	0.0	T	0.5	1.0	1.4	1.3	3.3	4.1	1.6	0.9	0.0	0.0	0.0
Brookline, N.H.	250	1901-05 1910-18	14	0.0	0.0	0.1	1.0	5.0	4.2	8.4	8.2	14.4	10.8	8.1	0.5	0.3	0.0
Buffalo, N.Y.	767	1917-36	20	0.0	0.2	0.2	0.6	1.7	2.6	4.2	4.4	3.4	2.9	1.1	0.5	0.1	0.0
Burlington, Vt.	404	1906-37	31		0.0		1.0		3.5		5.5		6.2		0.7		0.0
Cairo, N.Y.	340	1924-36	13	0.0	0.0	T	T	0.9	2.3	2.7	5.3	6.4	6.1	1.7	0.1	0.0	0.0
Canton, Conn.	900	1894-23	30	0.0	0.0	T	0.7	3.2	4.3	3.3	7.3	8.6	7.2	2.9	0.3	0.0	0.0
Canton, N.Y.	448	1906-36	30	0.0	0.0	0.6	1.2	3.5	3.6	4.9	5.1	7.1	6.2	4.3	1.1	0.0	0.0
Cambridge, Mass.	74	1893-00	8	0.0	0.0	0.0	0.3	3.0	2.5	3.1	3.9	9.8	4.9	0.6	0.1	0.0	0.0
°Cavendish, Vt.	800	1903-36+	32	0.0	0.0	0.8	2.2	5.1	8.1	13.3	14.7	20.0	22.5	17.7	7.8	1.3	0.0
Cazenovia, N.Y.	1200	1915-21	6	0.0	0.1	1.0	0.4	8.0	9.5	9.7	9.2	13.4	11.7	13.3	3.0	0.0	0.0
Chasm Falls, N.Y.	1100	1927-36	10	0.0	T	1.2	2.4	4.9	7.6	9.3	13.6	16.1	16.5	15.6	10.7	0.6	T
°Chatham, N.Y.	470	1904-20	17	0.0	0.0	0.4	0.2	1.9	2.4	3.2	3.5	6.9	5.5	2.8	0.6	0.1	0.0
Chazy, N.Y.	200	1922-35	8	0.0	0.0	0.0	0.5	2.8	5.7	7.4	8.6	7.0	6.4	5.4	3.0	0.0	0.0
Chelsea, Vt.	1070	1901-36+	31	0.0	0.1	1.8	2.7	6.6	9.2	14.4	14.7	27.5	20.7	21.5	12.5	2.8	0.2
Chestnut Hill, Mass.	124	1894-02+	8	0.0	0.0	0.1	0.6	1.2	1.4	2.3	7.6	11.2	5.4	3.1	0.0	0.0	0.0
Colchester, Conn.	460	1893-36	44	0.0	T	0.1	0.6	1.7	1.8	1.5	3.0	4.0	2.9	0.8	T	T	T
Concord, N.H.	350	1894-33	40		0.0		1.2		4.2		9.2		9.3		0.9		0.0
Concord, Mass.	139	1894-36+	40	0.0	0.0	0.1	0.6	2.0	3.4	3.8	4.9	8.0	5.6	2.3	0.1	T	T
Cooperstown, N.Y.	1200	1889-36+	40	0.0	0.0	1.0	0.8	3.5	4.4	4.8	7.0	9.0	7.9	5.5	1.1	0.4	0.0
Cornish, Maine	370	1896-24	29	0.0	0.0	0.3	2.5	6.9	9.9	12.6	15.1	22.2	20.6	17.2	7.8	2.0	T

Table 4--Average depths of snow-cover in inches at given dates--Continued

[° = stations for which we also have averages of seven daily readings centered on the 15th and end of each month, used in making the expectancy-diagrams; + = broken record with many gaps]

Station	Altitude, feet	Period	Total record, years	Oct. 15	Oct. 31	Nov. 15	Nov. 30	Dec. 15	Dec. 31	Jan. 15	Jan. 31	Feb. 15	Feb. 28-29	Mar. 15	Mar. 31	Apr. 15	Apr. 30
Cornwall, Vt.	504	1893-36+	34	0.0	0.0	1.1	1.4	3.1	4.0	5.1	6.7	10.0	5.9	2.8	1.0	0.1	0.0
Cream Hill, Conn.	1300	1896-36	40	0.0	T	0.3	0.9	3.5	3.7	5.2	7.0	10.3	8.6	4.7	0.8	0.1	0.0
°Cutchogue, N.Y.	32	1899-36	38	0.0	T	0.0	T	1.0	0.7	0.6	1.2	2.3	1.0	0.4	0.1	0.1	0.0
Danforth, Maine	386	1905-35+	22	0.0	0.0	1.8	2.3	7.6	12.1	14.3	15.3	19.0	18.2	17.4	7.2	1.3	0.0
°Dannemora, N.Y.	1440	1906-36	31	0.0	0.0	1.3	2.7	5.8	8.3	10.1	12.2	17.7	16.7	14.1	7.7	1.0	0.1
Dansville, N.Y.	703	1917-36+	20	0.0	0.0	0.0	0.2	0.3	0.7	1.4	2.9	0.6	0.3	0.5	0.2	0.0	0.0
Delhi, N.Y.	1460	1925-36	12	0.0	0.0	0.2	0.5	0.9	4.5	4.2	5.5	8.6	3.7	3.0	0.4	T	0.0
°De Ruyter, N.Y.	1365	1903-24	21	0.0	T	0.7	1.3	3.2	5.1	8.9	9.7	12.0	10.7	7.6	1.7	T	0.0
Dixville, Notch, N.H.	1650	1931-36	6	0.2	0.1	3.4	1.8	6.2	10.6	9.4	19.2	20.0	27.3	21.8	14.6	4.0	0.1
Dolgeville, N.Y.	685	1920-36	17	0.0	0.0	1.1	0.7	2.8	5.9	8.9	10.3	15.4	12.3	9.6	3.9	0.6	0.0
Durham, N.H.	83	1901-36+	31	0.0	0.0	0.1	0.4	1.7	3.3	6.0	6.4	9.4	7.4	4.4	1.1	0.2	0.0
East Hartland, Conn.	1220	1916-36	21	0.0	0.0	T	0.7	2.2	3.6	3.1	9.0	8.2	9.5	9.4	3.1	T	0.7
Eastport, Maine	53	1893-36	43		T		0.5		2.4		4.4		5.1		0.9		T
East Templeton, Mass.	1200	1894-06	13	0.0	0.0	0.8	2.9	3.4	4.1	4.6	7.9	12.3	7.8	4.1	1.9	0.1	0.0
Edmeston, N.Y.	1200	1911-15	5	0.0	T	0.0	1.0	4.6	8.0	4.8	2.9	11.3	6.8	4.4	0.2	T	0.0
Elba, N.Y.	750	1900-19	12	0.0	0.0	1.8	1.6	5.5	5.1	5.1	8.0	12.5	6.8	5.8	0.6	1.2	0.0
°Elmira, N.Y.	863	1912-36+	23	T	T	T	0.1	1.3	1.5	2.8	2.7	2.8	2.0	0.8	0.2	0.1	T
°Enosburg Falls, Vt.	422	1904-36	33	0.0	T	0.8	1.3	3.4	5.2	6.1	8.0	9.2	8.3	5.4	1.5	0.1	0.0
Eustis, Maine	450	1911-36	26	0.1	2.4	3.6	6.3	11.1	15.5	18.9	23.5	24.7	24.8	15.6	5.8	0.1	T
Fairfield, Maine	90	1888-08+	17	0.0	0.0	0.0	1.7	1.7	6.3	12.9	15.9	19.9	17.0	4.6	1.1	0.0	0.0
Farmington, Maine	425	1893-36	44	0.0	0.1	1.1	2.4	6.3	10.3	14.4	18.5	24.4	23.7	20.7	10.2	3.2	T
°Fayetteville, N.Y.	530	1901-18	17	T	T	0.8	0.6	3.6	2.8	4.1	3.6	6.3	2.9	2.1	0.3	T	T
°Fitchburg, Mass.	402	1894-36	43	0.0	0.0	0.2	1.0	2.9	3.4	5.2	7.2	10.8	6.6	2.6	0.2	0.2	0.0
Franklin, N.H.	390	1921-36	16	0.0	0.0	0.4	1.6	2.7	5.0	9.7	13.8	17.8	18.7	12.1	3.7	0.0	0.0
°Franklinville, N.Y.	1600	1896-09 1931-35	19	T	T	0.8	0.6	3.6	2.8	4.1	3.6	6.3	2.9	2.1	0.3	T	T
°Fredonia, N.Y.	765	1914-36	23	0.0	0.2	0.4	1.2	2.3	2.4	3.6	2.6	2.7	2.0	1.0	0.3	T	0.0
Flushing, N.Y.	60	1916-36	21	0.0	T	T	0.0	0.9	0.6	1.2	1.8	2.3	1.4	0.2	0.0	T	0.0
Gabriels, N.Y.	1750	1900-36+	29	0.0	0.0	3.0	3.8	7.1	10.9	12.8	16.2	19.9	19.2	19.1	10.0	1.7	0.2
Gardiner, Maine	139	1893-35+	24	0.0	0.0	0.9	1.6	4.0	6.5	9.0	11.6	13.0	13.7	10.9	3.2	0.7	0.0
Garfield, Vt.	1300	1919-32+	9	0.0	0.0	1.3	4.8	5.7	16.1	12.9	19.7	21.2	26.0	35.5	17.3	12.1	0.0
Glencliff, N.H.	1650	1909-36+	19	0.0	0.0	1.3	2.0	4.2	6.6	7.2	11.4	11.3	15.9	11.7	8.0	2.0	0.0
Glenham, N.Y.	170	1932-36	5	0.0	0.0	0.0	T	1.2	1.4	0.2	4.7	6.3	6.4	0.3	0.0	0.0	0.0
Glens Falls, N.Y.	349	1892-33	41	0.0	T	0.4	0.8	3.8	5.2	8.9	10.4	14.1	11.7	7.2	1.9	0.1	0.0
Gloucester, Mass.	15	1930-36	7	0.0	0.0	0.0	0.0	0.7	1.8	1.1	5.6	5.0	6.8	0.3	0.0	0.0	0.0
°Grafton, N.H.	863	1893-17	25	0.0	0.0	1.4	1.4	4.9	6.4	9.9	12.4	18.2	16.9	11.3	4.1	0.4	0.0
Greenfield, Mass.	165	1929-36	8	0.0	0.0	0.0	T	1.4	2.4	4.4	7.9	11.8	9.4	2.0	0.3	0.0	0.0
Griffen Corners, N.Y.	2250	1900-13+	13	0.0	T	3.7	1.4	4.6	3.2	3.6	3.7	4.3	3.1	2.0	0.5	T	0.0
Groton, Mass.	325	1893-08	16	0.0	0.0	0.1	1.5	3.8	4.5	5.8	10.1	13.1	9.9	4.0	0.1	0.1	T
Hanover, N.H.	603	1893-36+	34	0.0	0.0	0.3	1.5	3.0	4.1	8.8	10.0	13.6	10.1	7.5	7.2	0.7	0.0
Hartford, Conn.	159	1921-36	17	-	-	-	0.0	-	1.8	-	3.2	-	2.4	-	-	-	-
Hartland, Vt.	665	1893-01	9	0.0	0.6	0.8	2.0	4.5	6.3	10.3	14.1	17.2	17.1	14.1	7.6	0.5	0.0
°Haverhill, Mass.	50	1900-36+	36	0.0	0.0	T	0.2	2.0	2.3	3.5	4.5	7.0	3.8	1.8	0.2	0.1	0.0
Hemlock Lake, N.Y.	920	1900-37+	19	0.0	T	0.1	0.4	2.0	0.9	3.6	5.1	2.5	1.7	0.1	0.2	0.0	0.3
High Market, N.Y.	1786	1924-36+	12	0.0	0.5	0.0	0.5	9.2	13.9	21.3	26.0	29.5	31.4	29.6	12.5	0.9	0.3
Hiram, Maine	375	1930-36	7	0.0	0.0	0.0	0.2	2.0	7.6	13.1	22.1	21.6	29.0	23.5	9.9	2.5	0.0
Hoosac Tunnel, Mass.	800	1931-36	6	0.0	0.0	0.7	0.8	2.6	1.8	5.3	12.6	18.4	18.0	11.1	7.2	0.3	0.0
Holyoke, Mass.	90	1905-36	12	0.0	0.0	0.4	T	2.2	2.1	2.6	6.8	10.6	9.2	2.6	0.4	0.0	0.0
Houlton, Maine	364	1902-36+	26	0.0	T	1.6	2.7	6.8	11.9	14.0	25.4	27.4	30.2	16.5	8.6	2.1	T
Hyde Park, Vt.	576	1892-93 1912-18	8	0.0	0.0	1.2	1.9	9.0	11.0	16.3	14.3	13.9	15.3	10.3	0.7	1.3	0.0
°Indian Lake, N.Y.	1660	1899-24+	23	T	T	1.2	3.4	5.0	7.2	13.3	13.2	16.4	16.2	17.8	5.4	1.7	T
Ithaca, N.Y.	836	1900-36	37	0.0	T	0.2	0.3	2.6	2.2	3.4	3.7	3.3	2.0	1.0	0.2	0.0	0.0
Jackman, Maine	1180	1923-36+	13	T	T	2.0	2.7	-	14.1	7.5	25.6	8.5	28.6	-	15.1	-	3.3
Jacksonville, Vt.	1000	1893-11	19	0.0	0.3	2.6	3.1	7.9	8.5	9.6	13.5	18.3	16.9	10.6	6.2	0.2	0.0
Jamestown, N.Y.	1390	1895-09 1922-36	30	0.0	T	1.2	1.7	3.8	4.6	6.2	7.8	8.3	6.6	2.5	0.4	T	0.0

Table 4--Average depths of snow-cover in inches at given dates--Continued

[° = stations for which we also have averages of seven daily readings centered on the 15th and end of each month, used in making the expectancy-diagrams; + = broken record with many gaps]

Station	Altitude, feet	Period	Total record, years	Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.	
				15	31	15	30	15	31	15	31	15	28-29	15	31	15	30
Jeffersonville, N.Y.	1240	1903-36	34	0.0	0.0	1.0	0.4	2.9	3.4	4.6	6.5	8.7	7.0	4.2	0.2	0.0	0.0
Keene, N.H.	550	1893-31	39	0.0	0.0	0.6	1.3	3.6	4.0	6.1	7.7	10.6	8.4	4.4	0.4	0.0	0.0
Keene Valley, N.Y.	1012	1899-36	20	0.0	0.0	1.7	3.0	5.9	6.9	7.6	6.3	10.2	6.2	4.8	1.3	0.0	0.0
King Ferry, N.Y.	392	1900-15	15	T	0.1	0.5	0.9	4.6	2.9	5.5	4.5	5.2	3.3	2.7	0.3	0.2	0.0
°Lake Placid, N.Y.	1864	1909-28	23	0.0	0.1	0.9	4.6	8.0	10.0	13.4	14.7	19.2	18.3	16.7	10.5	1.5	T
Lancaster, N.H.	1100	1893-98+	5	0.0	0.0	1.4	3.2	3.0	8.2	9.6	15.4	17.6	22.0	18.6	8.2	1.0	0.0
Lawrence, Mass.	57	1893-36	44	0.0	T	0.5	2.1	2.8	4.3	4.8	7.4	4.6	1.6	0.1	0.1	0.0	0.0
Lawrenceville, N.Y.	482	1931-36	6	0.0	0.0	0.2	0.4	2.6	5.0	4.1	5.4	5.5	8.2	4.0	0.0	0.0	0.0
Leeds, Mass.	390	1893-00	8	0.0	0.0	0.3	3.0	1.8	3.4	5.9	12.6	14.8	11.2	5.1	1.9	T	0.0
Leominster, Mass.	540	1901-33	33	0.0	0.0	0.2	0.8	2.5	3.1	4.4	4.6	7.1	5.2	2.8	0.2	0.3	0.0
Letchworth Park, N.Y.	1260	1912-37+	24	0.0	T	0.4	0.7	2.1	3.6	6.0	7.4	4.9	3.6	2.1	T	T	0.0
Lewiston, Maine	182	1906-36	31	0.0	0.0	0.8	1.3	3.8	6.2	9.3	13.3	17.8	15.7	6.8	1.4	0.1	T
Liberty, N.Y.	2000	1899-18+	13	0.0	0.0	2.4	1.1	5.6	3.6	5.9	6.9	11.9	6.9	8.9	0.4	0.0	0.2
Little Falls, Sta. No. 1, N.Y.	890	1896-37+	39	0.0	0.0	1.0	1.2	4.4	7.4	10.3	12.7	16.0	11.5	6.2	1.5	0.1	0.0
°Little Falls, Sta. No. 2, N.Y.	375	1920-36	16	T	T	0.2	0.4	1.2	2.8	4.8	7.9	7.9	6.7	2.6	0.4	T	T
Littleton, N.H.	1400	1891-04+ 1929-35	17	0.0	0.0	1.5	2.4	5.1	7.1	9.4	12.0	14.4	13.8	10.2	5.3	1.0	0.0
Lockport, N.Y.	520	1911-37	26	0.0	0.0	0.3	0.2	1.9	2.3	3.4	3.8	3.3	2.7	1.4	0.2	T	0.0
Lowville, N.Y.	900	1890-08+ 1912-27	33	0.0	0.1	1.0	3.0	7.8	9.7	10.7	12.3	14.8	13.1	8.3	4.2	0.4	0.0
Ludlow Center, Mass.	239	1893-06+	8	0.0	0.0	0.0	0.4	4.0	3.8	3.7	11.3	12.9	10.6	5.7	0.3	0.0	0.0
Lyons, N.Y.	426	1901-07	7	0.0	0.0	0.9	0.6	6.1	3.3	5.6	6.7	7.3	5.0	1.7	T	0.1	0.0
Madison, Maine	257	1893-36+	25	0.0	0.0	1.0	2.2	5.2	10.2	14.1	20.3	27.7	28.5	16.9	8.0	1.5	0.0
Mansfield, Mass.	190	1893-99	7	0.0	0.0	0.3	4.1	2.0	1.9	2.8	7.6	8.0	3.7	0.6	1.4	T	0.0
Middleboro, Mass.	53	1893-15	23	0.0	0.0	0.0	0.9	1.2	0.9	1.6	2.0	2.2	1.0	0.5	T	T	0.0
Middle Dam, Maine	1430	1926-36+	10	0.0	T	0.8	2.5	7.1	10.7	16.0	20.8	25.0	26.7	25.7	21.3	15.5	0.9
Middletown, N.Y.	700	1900-07	8	0.0	0.0	1.1	0.1	4.8	1.2	2.5	4.8	5.8	4.3	1.7	T	0.0	0.0
Millbury, Mass.	330	1930-36	7	0.0	0.0	0.1	0.2	1.4	3.1	2.5	9.8	7.1	6.8	0.5	0.2	T	0.0
Millinocket, Maine	388	1903-36	34	0.0	0.0	1.6	3.5	9.1	12.5	18.4	22.4	27.7	29.1	27.5	19.0	5.8	1.5
Moira, N.Y.	420	1900-29	30	0.0	0.0	2.2	3.9	5.9	7.1	9.9	14.1	19.7	16.7	12.0	5.1	0.5	0.0
°Monson, Mass.	420	1893-11	19	0.0	0.0	0.3	1.8	3.2	1.7	2.3	4.9	6.1	3.0	1.6	0.1	0.0	0.0
Morrisville, N.Y.	1325	1913-36+	24	0.0	0.0	0.8	0.9	4.8	6.7	9.3	11.4	13.1	11.0	6.9	2.6	0.1	0.0
Mt. Hope, N.Y.	200	1900-29+	20	0.0	0.0	0.3	T	3.9	1.3	1.8	3.4	4.3	2.0	2.0	0.0	0.0	0.0
Mt. McGregor, N.Y.	1080	1916-20 1929-36	18	0.0	0.0	0.2	0.9	2.7	5.8	9.4	15.9	17.1	15.7	9.8	3.6	0.7	0.0
Mt. Tom, Mass.	199	1901-08	7	0.0	0.0	0.4	0.0	5.6	3.6	7.1	8.4	9.3	6.6	6.0	1.0	0.0	0.0
Mt. Vernon, Mass.	155	1914-36	22	0.0	0.0	0.0	0.0	1.8	1.2	1.7	3.1	3.2	2.3	0.7	0.0	0.0	0.0
Mt. Vernon, N.Y.	155	1914-36	22	0.0	0.0	0.0	0.0	1.8	1.2	1.7	3.1	3.2	2.3	0.7	0.0	0.0	0.0
Mt. Washington, N.H.	6280	1933-39	7	0.9	1.1	4.4	5.9	7.7	9.6	10.6	15.1	19.4	20.2	21.8	17.7	13.3	4.9
Nashua, N.H.	125	1898-16+	16	0.0	0.0	0.0	1.2	2.7	2.5	4.3	4.9	9.5	4.1	3.2	0.0	0.0	0.0
Nehasane, N.Y.	1720	1907-15	8	0.0	T	4.9	6.4	12.6	16.6	18.9	22.1	28.7	29.5	27.7	19.2	7.2	0.0
New Bedford, Mass.	63	1894-36+	20	0.0	0.0	0.0	0.8	0.7	0.5	1.1	2.2	3.5	2.3	0.9	0.4	0.2	0.0
New Haven, Conn.	68	1893-37	45	0.0	0.1	T	0.1	1.5	2.3	0.2	1.6	3.1	0.1	0.6	0.0	0.0	T
New Lisbon, N.Y.	1234	1900-23+	22	0.0	T	1.1	1.4	4.7	4.2	7.0	5.6	8.4	5.1	4.6	0.9	0.1	0.0
Newport, N.H.	790	1930-36	7	0.0	0.0	0.1	0.1	1.0	3.9	5.0	10.3	12.1	12.0	8.5	4.1	1.2	0.0
Newton, N.H.	200	1890-18	28	0.0	0.0	0.1	0.7	2.7	3.2	3.7	3.5	8.9	6.0	3.1	0.2	0.0	0.0
°New York, N.Y. (Battery Park)	5	1893-37	45	0.0	0.0	T	0.3	0.8	0.7	1.0	1.9	2.2	0.9	0.5	0.0	0.0	0.0
Norfolk, Mass.	44	1903-15	12	0.0	0.0	0.0	0.1	1.0	2.2	3.7	3.2	4.1	2.0	0.2	0.0	0.0	0.0
No. Billerica, Mass.	125	1893-10	17	0.0	0.0	0.2	1.1	3.4	2.8	5.0	5.7	9.2	4.1	3.4	0.2	0.1	0.0
No. Bridgeton, Maine	450	1893-36	43	0.0	0.0	1.2	2.1	5.6	9.0	13.0	17.9	22.2	24.2	15.8	7.7	2.0	0.4
Northampton, Mass.	205	1908-12	4	0.0	0.0	1.0	0.8	1.5	3.8	8.7	3.5	6.8	3.8	0.3	0.0	0.0	0.0
North Creek, N.Y.	1014	1907-15	8	0.0	0.0	0.6	1.5	9.5	10.6	12.2	15.8	16.8	21.5	18.6	9.0	0.0	0.0
North Lake, N.Y.	1833	1905-37	32	0.1	0.3	3.5	4.9	11.1	17.3	22.8	29.5	32.9	33.2	35.4	22.8	12.0	5.4
Norwich, Vt.	1150	1892-24	30	0.0	0.0	0.9	2.0	4.4	6.4	8.8	11.6	15.5	14.2	8.2	2.7	0.3	0.0

Table 4--Average depths of snow-cover in inches at given dates--Continued

[° = stations for which we also have averages of seven daily readings centered on the 15th and end of each month, used in making the expectancy-diagrams; + = broken record with many gaps]

Station	Altitude, feet	Period	Total record, years	Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.	
				15	31	15	30	15	31	15	31	15	28-29	15	31	15	30
Old Town, Maine	108	1921-36	15	0.0	0.0	0.6	0.9	1.9	6.5	8.3	8.9	11.2	8.8	6.6	1.9	T	T
Oswego, N.Y.	335	1893-37	44	0.0	0.0	0.4	1.0	3.6	4.7	6.8	8.3	9.5	8.3	5.2	0.5	0.2	0.0
Palermo, N.Y.	460	1899-15	15	0.0	0.2	0.5	0.7	7.2	10.0	8.5	8.5	17.0	12.8	12.4	1.2	T	0.0
Perry City, N.Y.	1038	1899-13	14	0.0	0.1	1.0	1.6	4.8	4.4	7.0	6.5	8.7	6.1	4.7	0.2	0.3	0.0
Perrysburg, N.Y.	1500	1915-23	9	0.0	0.2	1.7	2.0	6.3	6.7	13.0	8.5	10.0	6.4	2.1	0.5	0.0	0.0
Peterboro, N.H.	744	1892-02	11	0.0	0.0	0.8	3.0	6.2	4.6	4.4	12.3	18.0	16.0	7.6	3.6	0.3	0.0
Philadelphia, N.Y.	485	1907-36	30	0.0	0.0	0.6	1.5	5.3	6.1	8.7	9.2	12.0	9.2	5.4	1.6	T	0.0
°Pinkham Notch, N.H.	2000	1929-39	11	0.2	0.6	1.6	2.1	7.6	14.5	17.6	26.8	30.7	33.6	37.4	28.2	17.4	3.8
Pittsfield, Mass.	1037	1896-36	41	0.0	T	1.0	0.9	0.2	2.0	1.2	3.5	2.4	5.2	0.7	2.4	T	0.0
Pittsburg, N.H.	1660	1917-36	20	0.3	0.4	2.5	4.7	9.2	14.4	19.9	25.7	30.0	32.1	31.1	26.9	17.0	6.5
°Plymouth, N.H.	500	1900-36	37	0.0	0.0	0.7	1.2	4.4	7.0	13.1	15.7	19.7	17.9	12.6	3.5	0.4	0.0
Port Jervis, N.Y.	550	1899-35+	36	0.0	0.0	0.5	0.3	3.7	2.9	4.6	5.1	5.7	3.0	1.2	T	0.0	0.0
Presque Isle, Maine	606	1916-36	21		T	1.6	2.9	8.4	12.4	15.9	20.2	24.6	23.9	25.3	13.9	2.9	T
Providence, R.I.	160	1905-36	32			T		0.7		2.2		1.6		0.1		0.0	
Racquette Lake, N.Y.	1775	1908-29+	22	0.0	0.2	2.3	5.2	8.3	13.7	16.0	18.8	24.4	23.8	26.1	14.7	5.8	T
Rhinebeck, N.Y.	215	1916-25+	10	0.0	0.0	0.0	0.2	3.3	3.5	8.6	11.4	13.3	10.4	2.5	0.3	0.0	0.0
°Rifton, N.Y.	190	1921-36	15	0.0	0.0	T	0.1	0.2	3.4	6.1	6.1	8.3	6.6	0.9	0.6	T	0.0
Ripogenus, Maine	965	1925-36	12	0.7	0.0	1.3	4.6	4.8	16.6	25.7	35.1	30.4	32.0	33.1	26.0	11.5	4.1
Rochester, N.Y.	523	1892-36	45	0.0	0.1	0.4	0.6	2.9	2.6	4.8	5.3	5.6	4.8	2.9	0.4	0.2	0.1
Rochester, Vt.	825	1929-36	8	0.0	0.0	0.4	0.5	2.1	5.1	5.8	12.4	11.4	12.7	10.1	3.9	0.6	0.0
Rockport, Mass.	25	1902-35	34	0.0	0.0	T	T	0.2	1.4	0.8	1.1	2.9	1.3	0.6	0.2	T	0.0
Roxbury	107	1894-01	8	0.0	0.0	T	2.8	1.0	1.9	1.4	4.1	7.9	0.8	1.2	T	0.0	0.0
Roxbury, N.Y.	1490	1915-36+	22	0.0	0.1	0.3	0.8	3.3	4.3	6.9	8.5	10.5	9.5	7.4	3.2	0.6	0.0
Rumford, Maine	506	1900-36	37	0.0	T	1.0	1.9	5.2	8.1	12.0	12.9	16.4	14.7	8.9	2.2	0.0	0.0
Rutland, Vt.	610	1918-31	14	0.0	0.0	0.4	1.7	0.2	3.8	4.8	6.4	10.8	0.0	0.2	1.5	0.0	0.6
Rutland, Mass.	1160	1908-22+	17	0.0	0.0	0.5	1.2	4.0	2.2	4.1	4.7	9.6	5.1	5.4	1.8	0.7	0.0
°Salisbury, N.Y.	1300	1896-36+	41	0.0	0.0	1.7	1.6	5.6	14.9	15.2	18.1	23.7	21.1	15.4	7.4	1.0	0.0
Sanbornton, N.H.	830	1893-03	11	0.0	0.0	0.0	1.8	5.5	8.0	10.9	14.9	19.7	17.4	14.3	8.9	1.0	0.0
Saranac Lake, N.Y.	1620	1899-09+	11	0.0	0.0	4.7	6.2	7.0	8.9	12.7	11.8	13.3	9.7	5.3	2.3	0.5	0.0
Scarsdale, N.Y.	270	1903-36	34	0.0	0.0	0.2	0.0	2.5	1.7	2.0	3.5	4.0	2.0	1.1	0.0	0.0	0.0
Searsburg Mt., Vt.	2360	1930-36	7	0.0	0.1	1.5	1.9	4.2	6.9	10.3	20.0	23.8	29.6	29.6	21.1	15.1	3.5
Sharon Springs, N.Y.	821	1913-36+	24	0.0	0.0	0.1	0.3	2.5	3.3	5.0	9.0	9.4	7.7	5.7	1.0	0.0	0.0
Shelburne Falls, Mass.	400	1930-36	7	0.0	0.0	0.1	0.3	1.9	3.4	6.8	12.4	17.5	15.8	7.0	1.2	0.5	0.0
Skaneateles, N.Y.	875	1917-36+	19	0.0	0.1	0.7	0.4	1.3	4.4	6.9	9.5	9.3	8.0	3.8	1.7	T	0.0
Somerset, Mass.	40	1894-22	29	0.0	0.0	T	1.0	2.0	1.3	3.0	3.6	5.3	1.2	1.2	0.1	T	0.0
Somerset, Vt.	2080	1913-36	24	0.0	0.0	0.8	2.4	5.2	8.6	14.8	20.0	26.4	25.9	24.9	17.6	10.8	3.2
South Egremont, Mass.	764	1902-11	10	0.0	0.0	0.3	1.3	5.1	4.8	9.2	7.0	17.4	3.3	6.3	0.0	0.0	0.0
Southampton, N.Y.	36	1900-17+	18	0.0	0.0	0.0	T	2.9	0.6	1.2	1.2	0.9	0.7	0.4	T	T	0.0
Southington, Conn.	140	1894-21	28	0.0	0.0	0.2	0.5	2.6	1.7	1.8	3.6	3.7	1.9	1.1	T	T	T
Springfield, Mass.	199	1898-36	39	0.0	0.0	0.1	0.3	1.9	1.6	3.2	3.6	7.3	5.0	1.0	T	0.0	0.0
St. Albans, Vt.	470	1930-36+	7	0.0	0.0	0.0	2.0	6.5	7.5	3.5	4.8	2.2	3.7	3.6	0.0	0.0	0.0
°St. Johnsbury, Vt.	711	1894-36	43	0.0	0.0	1.1	1.8	3.8	6.6	9.6	12.0	15.1	13.6	9.9	3.4	0.5	0.0
Stafford, N.Y.	900	1931-36	6	0.0	0.0	0.3	0.2	2.4	1.2	1.6	3.6	5.7	3.5	2.5	0.5	T	0.0
Stockbridge, Mass.	850	1930-36	7	0.0	0.0	0.7	T	0.7	2.2	3.4	7.3	9.0	9.5	3.0	0.7	0.1	0.0
Storrs, Conn.	640	1894-36	43	0.0	0.0	T	0.9	1.0	2.8	2.3	3.9	4.3	2.7	0.8	0.1	0.0	0.0
Stratford, N.H.	1000	1893-05	9	0.0	0.1	1.9	3.4	5.5	6.5	9.1	11.7	13.4	13.6	10.8	5.4	2.4	0.0
Syracuse, N.Y.	597	1902-36	35	0.0	T	0.4	0.3	2.8	2.9	5.2	4.3	5.2	2.8	2.4	0.3	T	0.0
Ticonderoga, N.Y.	340	1897-11+	12	0.0	0.0	1.1	0.8	4.7	4.1	9.1	8.0	10.9	6.0	3.7	0.6	0.8	0.0
The Forks, Maine	570	1902-33+	32	0.0	0.2	2.4	3.7	7.4	11.6	16.3	18.1	24.0	22.6	24.9	16.8	4.3	0.2
Tupper Lake, N.Y.	1720	1924-36+	12	0.0	T	0.9	0.6	2.7	5.8	6.2	12.2	12.1	11.9	7.4	3.0	0.7	0.0
Turners Falls, Mass.	200	1893-36+	44	0.0	0.0	0.2	0.7	2.4	3.0	5.4	7.0	10.4	7.4	2.8	1.2	T	T
Twin Mt., N.H.	1500	1927-33+	7	0.0	0.0	0.0	0.0	2.2	3.2	6.4	12.2	12.7	13.7	18.0	5.4	0.7	0.0
Upper Dam, Maine	1484	1926-36+	11	0.0	0.0	0.0	2.0	6.9	11.7	13.4	18.8	22.4	25.7	23.7	20.4	13.7	5.0
Van Buren, Maine	510	1902-27+	26	0.0	0.9	2.9	3.8	6.7	11.8	18.1	22.1	26.9	33.8	27.1	15.3	0.7	T
Vernon, Vt.	228	1895-36+	42	0.0	0.0	0.1	2.0	2.0	4.6	6.2	11.4	12.6	12.2	6.6	1.8	0.0	0.0
Volusia, N.Y.	1560	1899-19+	21	0.0	0.3	4.3	3.9	9.8	11.4	10.5	11.0	12.7	9.5	4.4	0.4	T	0.3
°Walden, N.Y.	400	1922-36	15	0.0	0.0	0.1	T	1.0	1.6	4.9	5.4	6.5	3.9	0.7	0.1	T	0.0

Table 4--Average depths of snow-cover in inches at given dates--Concluded

[° = stations for which we also have averages of seven daily readings centered on the 15th and end of each month, used in making the expectancy-diagrams; † = broken record with many gaps]

Station	Altitude, feet	Period	Total record, years	Oct.		Nov.		Dec.		Jan.		Feb.		Mar.		Apr.	
				15	31	15	30	15	31	15	31	15	28-29	15	31	15	30
°Wanakena, N.Y.	1500	1910-36	27	0.1	0.1	1.0	2.9	4.9	10.6	13.8	16.7	18.7	19.4	17.8	9.3	2.6	0.2
°Wappingers Falls, N.Y.	150	1899-36	32	0.0	0.0	0.1	0.3	1.2	1.6	3.8	4.9	6.2	3.6	1.5	0.1	T	0.0
Waterbury, Conn.	340	1893-36	41	0.0	0.0	0.2	0.7	2.6	2.4	2.6	5.0	5.3	3.1	0.8	T	0.0	0.0
Watertown, N.Y.	497	1891-36†	32	0.0	T	1.3	1.8	6.3	5.6	5.8	6.9	7.8	5.7	3.9	1.5	T	0.0
Waverly, N.Y.	824	1900-15†	16	0.0	0.0	0.3	0.6	3.1	3.3	4.7	2.9	3.9	2.1	1.5	0.0	0.0	0.0
Webster, Mass.	450	1893-07†	15	0.0	0.0	0.0	3.4	5.3	5.2	5.2	6.1	11.4	4.0	3.9	0.1	0.0	0.0
Wedgewood, N.Y.	1350	1900-21	22	0.0	0.1	0.7	0.8	4.4	4.5	6.4	6.0	7.8	5.5	3.8	0.1	0.1	0.0
Wells, Vt.	900	1893-20	28	0.0	0.0	1.7	0.9	4.2	3.8	7.2	6.3	12.2	9.5	7.4	6.3	0.0	0.0
West Lebanon, N.H.	340	1932-36	5	0.0	0.0	0.1	0.6	2.3	6.6	5.2	9.2	13.6	18.2	4.8	1.5	1.6	0.0
West Milan, N.H.	1016	1893-98	6	0.0	0.0	4.5	2.0	6.5	12.7	16.0	23.0	30.4	30.6	26.8	16.8	10.5	0.0
°West Point, N.Y.	386	1908-36	26	0.0	0.0	T	T	0.6	0.7	1.0	1.3	2.0	1.6	0.4	T	T	0.0
West Stewartstown, N.H.	1050	1930-36	7	0.0	0.0	1.0	1.0	2.7	6.8	9.1	21.1	21.1	28.2	21.6	15.8	7.8	0.5
Westfield, Mass.	475	1926-34	9	0.0	0.0	0.0	T	1.2	1.9	2.9	3.8	5.8	5.8	T	0.0	0.0	0.0
°Weston, Mass.	224	1896-36	40	0.0	0.0	0.1	0.9	2.4	2.1	2.9	6.1	8.0	5.2	1.4	0.1	T	0.0
White River Junction, Vt.	490	1918-36	19	0.0	0.0	0.1	1.0	2.3	6.9	8.2	9.5	10.5	11.9	5.0	1.8	0.4	0.0
Whitingham, Vt.	1450	1930-36	7	0.0	0.0	0.6	0.6	3.0	4.1	8.2	13.3	16.8	19.6	14.9	12.7	4.5	0.0
°Williamstown, Mass.	711	1889-36	48	0.0	T	0.4	0.6	2.7	2.4	3.5	4.2	5.8	3.8	2.1	0.3	T	0.0
Wilmington, Vt.	1640	1930-34	5	0.0	0.0	0.9	0.0	2.4	6.2	10.4	12.6	12.9	20.3	24.9	24.8	9.5	0.0
Winslow, Maine	90	1900-29†	30	0.0	T	1.3	1.9	5.4	7.2	10.0	11.5	16.6	13.2	5.9	1.3	0.2	0.0
Woodland, Maine	140	1918-36	19	0.0	T	0.3	1.9	2.5	8.2	11.5	11.6	17.8	15.8	11.1	2.8	0.4	0.0
Woodstock, Vt.	800	1896-36	41	0.0	0.0	0.8	2.5	4.5	9.2	8.9	16.3	16.4	18.6	13.5	7.8	1.0	0.0
Woodsville, N.H.	450	1919-33†	15	0.0	0.0	0.2	1.2	1.8	5.9	7.8	13.8	18.6	18.1	12.2	1.7	0.0	0.0
Worcester, Mass.	625	1893-36	44	0.0	T	0.2	0.8	2.3	3.1	3.9	5.5	7.2	5.7	3.0	0.1	0.1	0.0
York, N.Y.	760	1911-25	15	0.0	0.0	0.1	0.2	3.0	4.3	6.4	7.6	8.0	5.0	3.0	0.2	0.0	0.0

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[3] See [2].

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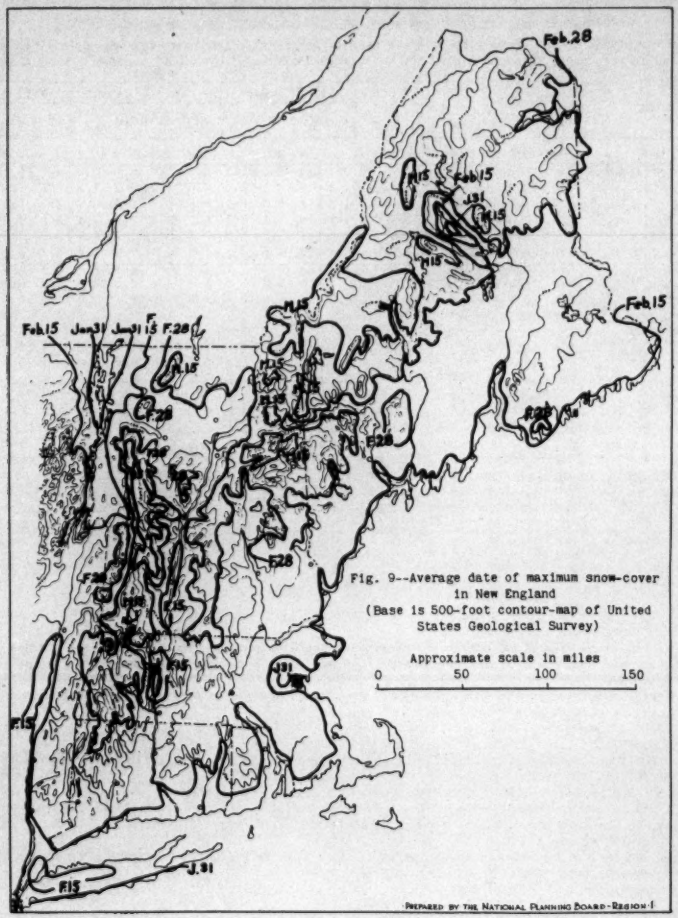
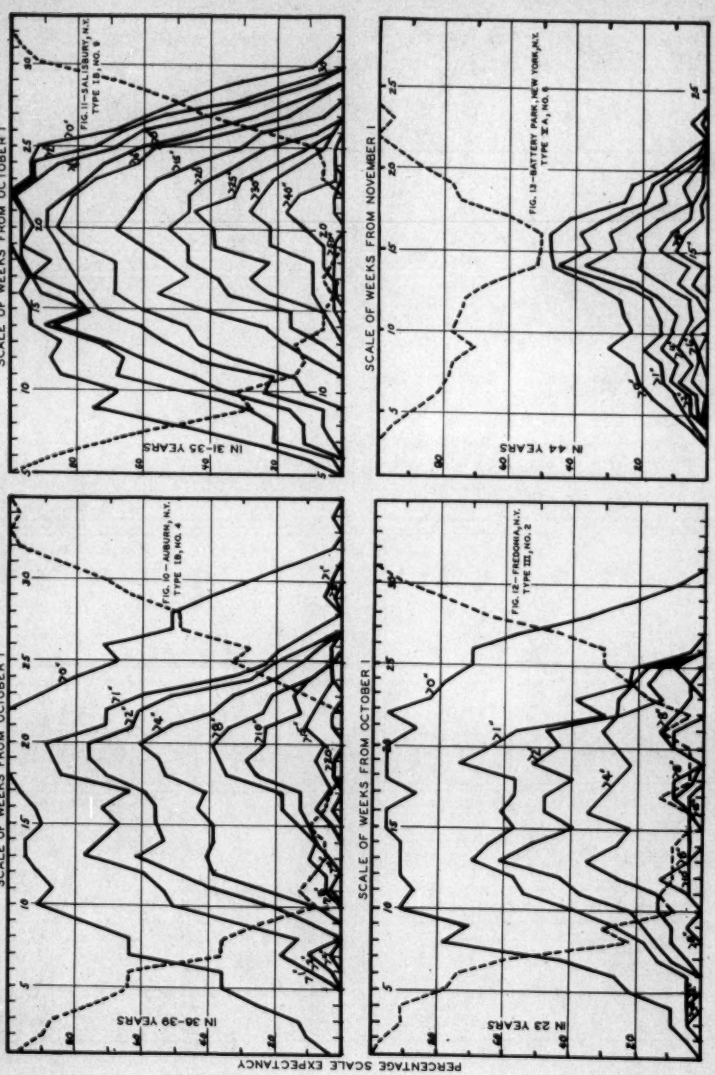
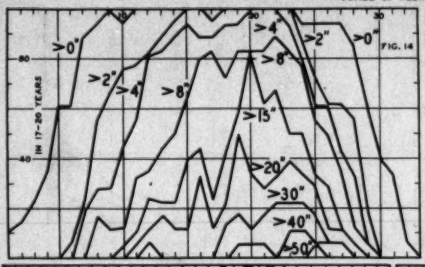


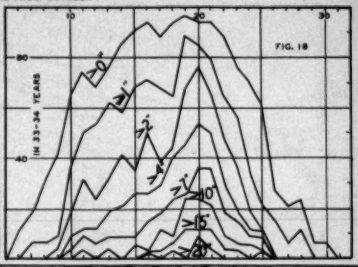
Fig. 9--Average date of maximum snow-cover in New England
(Base is 500-foot contour-map of United States Geological Survey)

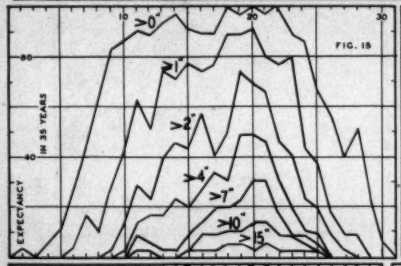

SCALE OF WEEKS FROM OCTOBER 1
SCALE OF WEEKS FROM NOVEMBER 1
PERCENTAGE SCALE EXPECTANCY
IN 36-39 YEARS
IN 31-35 YEARS
IN 23 YEARS
IN 44 YEARS
FIG. 10—AUBURN, N.Y. TYPE 1B, NO. 4
FIG. 11—SALISBURY, N.Y. TYPE 1B, NO. 9
FIG. 12—FREDONIA, N.Y. TYPE 1B1, NO. 2
FIG. 13—BATTERY PARK, NEW YORK, N.Y. TYPE 2C A, NO. 6

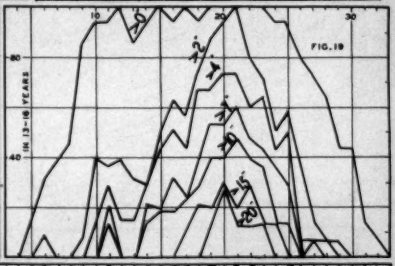
Figs. 10-13--Expectancy of average weekly depth of snow on ground

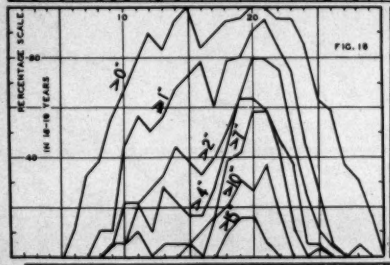
← SCALE OF WEEKS FROM OCTOBER 1 →

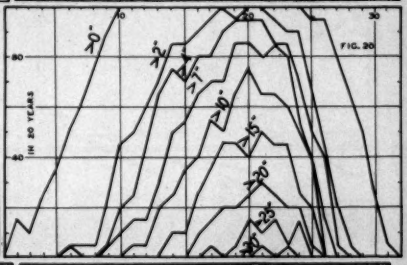


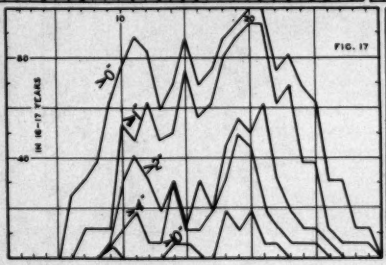


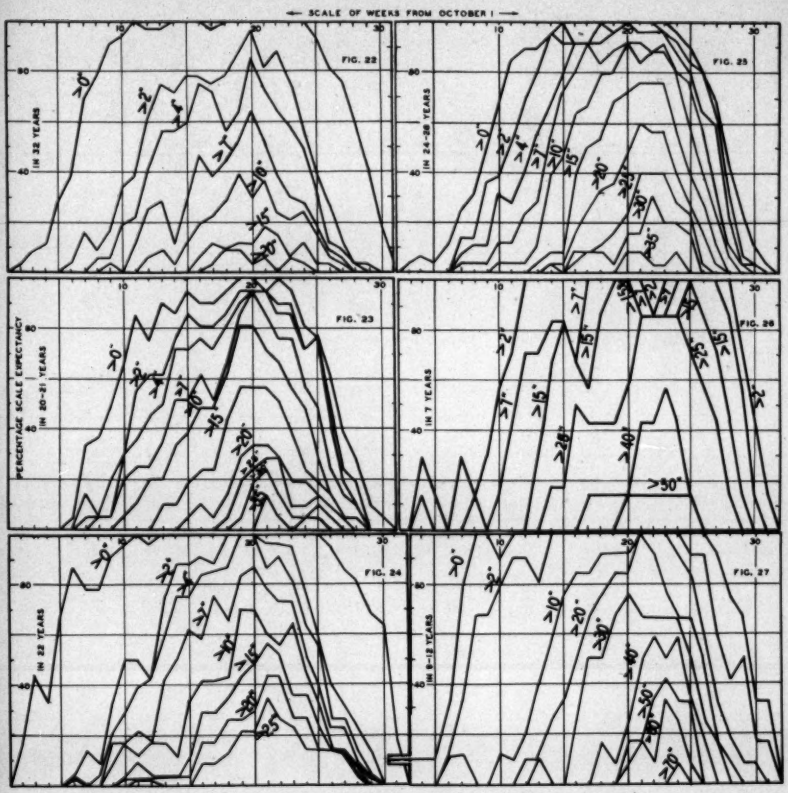






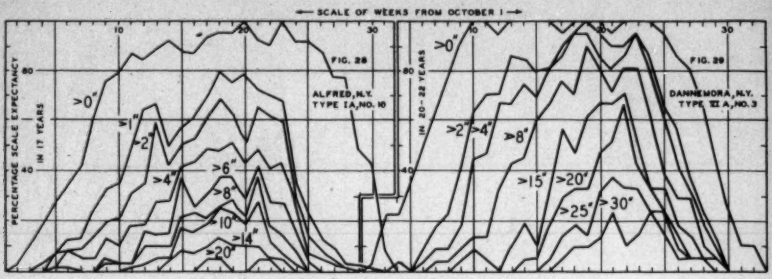






Figs. 14-27--Expectancy of average weekly depth of snow on ground

14--Lake Placid, N. Y., Type VI A, No. 1
16--Weston, Mass., Type B, No. 4
18--Haverhill, Mass., Type VII D, No. 2
20--St. Johnsbury, Vt., Type VIII, No. 5
22--Enosburg Falls, Vt., Type VIII, No. 11
24--Berlin, N. H., Type IX A, No. 12
26--Pinkham Notch, N. H., Type X, No. 6
15--Williamstown, Mass., Type VII B, No. 6
17--Monson, Mass., Type VII B, No. 6
19--Bar Harbor, Me., Type VII M, No. 6
21--Plymouth, N. H., Type VIII, No. 6
23--Grafton, N. H., Type VIII, No. 15
25--Cavendish, Vt., Type IX A, No. 13
27--Ashland, Me., Type XI, No. 6



Figs. 28-29--Expectancy of average weekly depth of snow on ground

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

SECTION OF TECTONOPHYSICS

REPORTS AND PAPERS

Washington, D.C.
April 25, 1940

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Reports and Papers

NEW MEASUREMENTS OF THE RIGIDITY OF ROCKS AT HIGH PRESSURE

Francis Birch and Dennison Bancroft

(Abstract)

Dynamical measurements of rigidity and velocity of distortional waves are presented for a few igneous rocks at pressures up to 9,000 kg/cm^2 and for a group of schists, gneisses, and sedimentary rocks from the Boston area at pressures up to 4,000 kg/cm^2. The effect of temperatures up to 150° C upon the velocity was determined at pressures of 4,300 kg/cm^2 and 8,600 kg/cm^2. The average temperature-coefficients of velocity between 30° and 150° C vary from -30×10^{-6} to to -160×10^{-6}, with the acid rocks usually showing the smallest changes. The velocities of shear-waves in quartz-muscovite schists, in chlorite schist, and in a compact argillite are found to be as high as or higher than the velocity in the average granite; the velocity in a dolomite is as high as in gabbro or diabase. The measurements are discussed with reference to the problem of identification of materials by seismic methods.

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AN ELECTRONIC INTERVAL-TIMER FOR LABORATORY SEISMOMETRY

Dennison Bancroft

In order to study the propagation of elastic disturbances in laboratory-size specimens, a device for measuring intervals of time of the order of 10^{-4} second has been developed. The instrument depends for its operation upon the measurement of the charge, Q, carried by a known current, i, in the unknown time, t. Determination of Q is accomplished by allowing the charge to accumulate on a condenser of known capacity. The potential to which the condenser is thus raised is measured by means of a vacuum-tube voltmeter, having extremely high input-impedance. This scheme eliminates the somewhat inconvenient ballistic galvanometer, for the readings are taken with a simple milliammeter. It is subject to the slight disadvantage that leakage from the condenser causes the milliammeter to drift, but it has been found that consistent readings can readily be obtained by observing the maximum deflection of the instrument, the latter being critically damped.

Having thus achieved a satisfactory arrangement for the measurement of Q, it remains to provide a high-speed switching-device, whereby the current may be turned on and off at the beginning and end of the interval to be measured. Switching circuits have been devised [see 1 of "References" at end of paper] which employ high-vacuum tubes, but it was felt that considerable simplification would result if the small gas-filled thyratrons (for example, type 2A4G) could be employed. It developed in the course of experimenting with these tubes that their firing characteristics are sufficiently consistent to permit their being used to measure extremely short intervals of time. The uncertainty which they thus introduce appears to be slightly less than 10^{-7} second. The switching circuit used is a development of one devised by Hull [2]. Its details appear in Figure 1.

The final problems which present themselves are the production of electrical pulses to define the beginning and end of the time-interval with the requisite precision, the transmission of these pulses to the timing device, and lastly their amplification to a point where they will operate the thyratrons. Crystal-phonograph pickups (from which the damping material had been removed) were found reasonably satisfactory for converting the mechanical displacement into an electrical pulse. Some trouble was encountered in making the front of the mechanical pulse sufficiently steep to define the interval with the requisite accuracy. Best results to date have been obtained by attaching a hardened-steel hemisphere to the specimen, and striking it with a hard hammer. To eliminate undesirable effects of the wave-train which inevitably follows the first pulse, the outputs of the two pulse-amplifiers were fed to auxiliary thyratrons whose firing set off the switching thyratrons by means of a single pulse of invariable shape.

It is proposed to calibrate the instrument in terms of the velocity of sound in a steel bar, but before relying too much upon such a calibration, it appeared imperative to investigate whether or not the velocity of a pulse in the steel bar corresponded to the so-called "bar-velocity." To check this point, experiments were carried out on a one-inch diameter piece of cold rolled steel, using a distance between pickups of 30 cm. The charge was measured by means of a ballistic galvanometer, calibrated in terms of its electrical and mechanical constants.

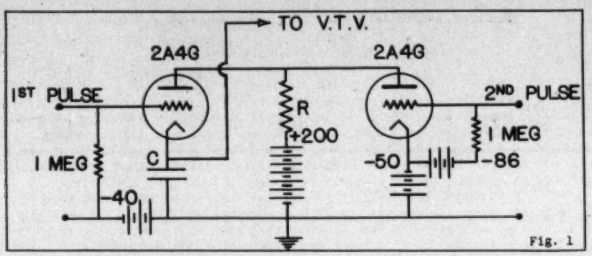

Fig. 1--Switching circuit employing hot-cathode thyratrons
[The elements R and C are so chosen that a potential of about ten volts is developed on C in the elapsed interval of time]

Current was estimated by steady-state measurements when the thyratron was in the conducting condition. The velocity thus obtained was 5.17×10^5 cm/sec, to compare with a value of 5.16×10^5 cm/sec found by resonance-measurements using a sample from the steel bar. The agreement is doubtless fortuitous, as the estimated error in our pulse velocity determination was nearly one per cent.

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VARIATION OF ELASTIC CONSTANTS WITH MOISTURE IN SOAPSTONE

John P. Delaney

The literature on elastic constants of rocks hardly mentions the possibility of a variation of these constants with the varying moisture-content of the specimens. The present paper proposes no precision value for the elastic constants of soapstone, nor does it offer a new method for elastic-constants determinations, nor does it even aim toward the high precision of past and present investigators in this important field. The paper is presented merely to suggest the possibility that the elastic constants of rocks, or at least of some rocks, might vary over a wide range as an effect of their moisture-content.

Zisman in his report of his thorough investigation into the elastic constants of rocks reviewed some of the annoying discrepancies in the values of these constants as reported by previous investigators. He concluded that these discrepancies were explicable not only by real differences in the specimens of the several rocks investigated but also by differences in the methods of the measurements, especially in the various ranges of the pressures applied. In checking his own results with those of Adams and Coker he observed that when he had shielded his specimens from the fluid used to transmit hydrostatic pressure his data showed closer agreement with the data of Adams and Coker. He interpreted this better agreement in terms of a changed distribution of pressure rather than in terms of changed elastic constants under the influence of moisture contained in the specimen.

The thorough investigations of Adams and Coker into the elastic constants of rocks, published over 30 years ago, are well known and might be regarded as classic in this important field. In scholarly procedure Adams and Coker analyzed the methods of previous investigators and they found that these methods could yield results that were merely approximate. They showed that the values of elasticity obtained by flexure-experiments might differ by very considerable amounts from those obtained by compressional methods, and in addition to their fine command of theory they had at their disposal testing machinery of refinement and fine precision. As a final precaution they examined carefully into the possibility of temperature-changes affecting their measurements of elastic constants and they found that the ordinary temperature-changes of the

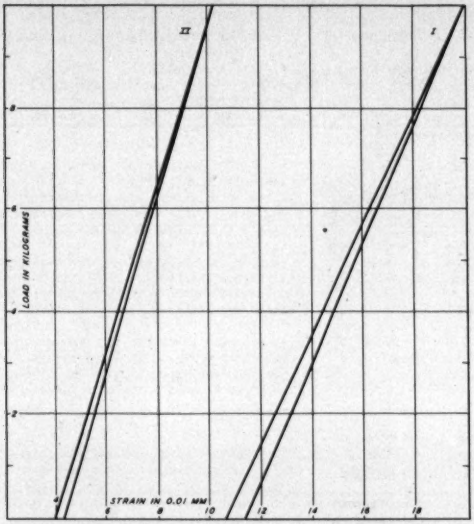

Fig. 1--Elastic hysteresis-curves for dry (II) and damp (I) soapstone

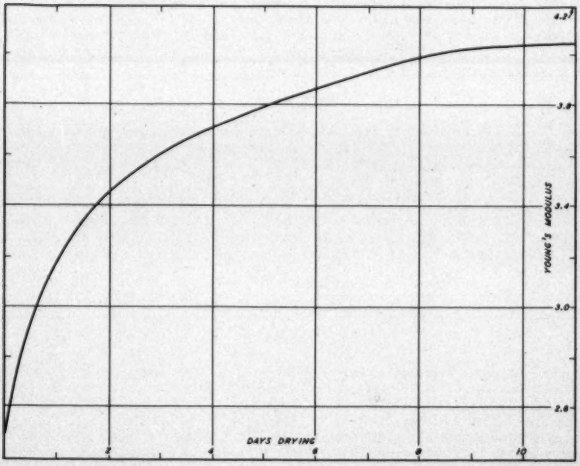

Fig. 2

laboratory could be neglected. Strangely enough they make no mention in their report of the possibility that the elastic constants of their specimens might vary with their content of moisture, a factor which might be as variable as the surrounding relative humidity.

Since the problem appears of some importance, especially in view of the serious discrepancies in the literature on the elastic constants of rocks, a preliminary series of tests was run using the simple flexure method on a fine specimen ready at hand, a shelf of soapstone in the physics laboratory at Loyola College, Baltimore. The shelf was 174.8 cm long, 15.3 cm wide, 3.29 cm thick, and of density 2.86.

Table 1

Hours after drying	Strain per kg stress cm	Young's Modulus
Dry	0.0054	4.48×10^{11}
1	0.0097	2.47×10^{11}
12	0.0082	3.02×10^{11}
24	0.0076	3.26×10^{11}
36	0.0073	3.39×10^{11}
48	0.0071	3.49×10^{11}
60	0.0070	3.54×10^{11}
72	0.0069	3.59×10^{11}
96	0.0067	3.69×10^{11}
120	0.0065	3.81×10^{11}
144	0.0064	3.88×10^{11}
168	0.0062	3.99×10^{11}
192	0.0061	4.05×10^{11}
216	0.0061	4.05×10^{11}
240	0.0060	4.13×10^{11}

After measurements were taken for Young's Modulus on this perfectly dry specimen, suspended in an uncomfortably dry laboratory, the shelf was removed and left in a trough under running water for 48 hours. It was then replaced as before and Young's Modulus was determined every 12 hours for ten days as the specimen slowly dryed. Each reading was obtained by averaging the results of stress and strain as the shelf was loaded and then unloaded, three times, kilogram by kilogram, up to ten kilograms. Young's Modulus for the dry specimen was found to be 4.48×10^{11} dynes per cm^2, and good elasticity was indicated by the narrow hysteresis-curve. After soaking, but superficially dry, the specimen showed much poorer elasticity as indicated by the wide hysteresis-curve, and Young's Modulus had fallen to 2.47×10^{11}.

Table 1 gives the daily readings for ten days. It is noted that even after ten days drying Young's Modulus had not yet returned to the initial value in the dry specimen. The curves appended show the hysteresis-values for the dry and wet stone and the variation of Young's Modulus as the specimen dried. If a physical significance for this variation might be suggested, possibly the moisture affects the intergranular binding of the specimen, possibly it supplies a sort of intercrystalline or intergranular lubrication. To correlate more closely the moisture-content with the change of elasticity, measurements for conductivity should have been taken simultaneously with the elastic measurements, and it is intended in further measurements so to correlate these measurements. Better still, the evaporation from a small specimen can be followed closely on an analytic balance. Both of these methods were tried with interesting results but not simultaneously with the data here presented and hence their value for present purposes would be questionable.

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FRACTURE AND FLOW IN STRESSED SOLIDS

Roy W. Goranson

This paper presents a correlation and interpretation of the various data concerning the phenomena of deformation, "flow" or creep, and rupture of a stressed solid, based on a consideration of the internal energy stored in the lattice structure of the material. The elastic or potential component of this internal energy is represented by a function having the characteristics of a Condon-Morse potential-energy diagram, and, if this were the only operative mechanism, release of this stored-up strain-energy would occur as rupture in the direction of greatest extension of the lattice structure. This strain-energy may, however, also be released by means of

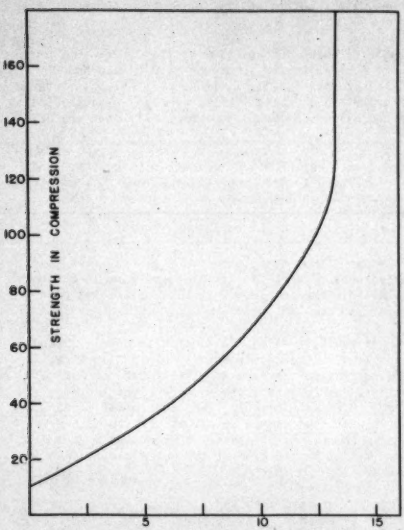

Fig. 1--Theoretical compressive strength of iron at 0° absolute as a function of hydrostatic confining pressure

a change-of-phase mechanism, solid to fluid to solid, wherein material is transferred from a region of high stress to a region of low stress. For this effect the work received by the system is converted into an "activation-energy" approximately equivalent to the heat of melting; and the generalized relations are expressed by the thermodynamic potential functions. The argument for these considerations is presented elsewhere [see 1 of "References" at end of paper].

These two mechanisms are generally combined. It should be noted, however, that the first type of deformation is an instantaneous effect whereas the latter is a function of time. Thus the specimen may fail elastically long before the second mechanism has had time to become operable if the load is applied rapidly.

Now if the solid is first compressed under higher hydrostatic (uniform) pressure before stressing it with non-uniform compressive load, it is deduced from the above hypothesis that the elastic compressive strength increases rapidly with increasing hydrostatic pressure, eventually tending toward infinity at some finite value of confining pressure.

To eliminate the complications introduced by the second type, or flow, mechanism we may take our system down to absolute zero temperature. The compressive strength of iron as a function of confining pressure at 0° absolute is plotted in Figure 1. It will be observed that the slope of the curve denoting compressive strength steepens rapidly, and finally becomes very steep at some finite value of the confining pressure. At very low temperatures release of strain-energy can then occur only by a collapse of the lattice structure, as by a solid A to solid B transition where the B-phase is a denser modification of A.

As the temperature is raised a state will eventually be attained above which the requisite "activation energy," that is, the necessary excess energy, has decreased to the point where the differential stress can initiate the solid to fluid to solid change-of-phase mechanism. For these conditions the solid deforms by flow from regions of high stress to regions of low stress. If the solid A is a stable form for these temperatures and pressures the transfer mechanism is from solid A to fluid to solid A. If, however, solid A is metastable for these conditions the reaction is solid A to fluid to solid B, where B is the stable modification. In this latter case the reaction will take place catastrophically if the change A to B occurs with liberation of considerable free energy.

Rocks are generally made up of several different crystalline substances. Let us assume that we have one containing crystals of "X" and of "Y." Here the flow-mechanism might be by solid "X" to fluid "X" which reacts with "Y" to form the compound "XY." This might be further complicated by introducing a solvent "Z"--as was done for the alabaster-water creep relations [1]. The result of solution and recrystallization under stress for this last case may be a change from the mixture of "X" and "Y" crystals to compounds such as "X'Y'Z'" and "X'Y'." This is apparently the mechanism for many of the metamorphic phenomena occurring in rocks.

The quantity that has been labelled "viscosity" or "pseudo-viscosity," in referring to flow in solids or to deformation in the Earth, is related to the "activation-energy" which is in turn a function of the differential stress. The required excess energy is roughly proportional to the ratio of melting point to the prevailing temperature in degrees absolute. Hence the higher the temperature the less is the differential stress needed to make the solid deform by flow. It

should be noted, however, that the melting point, and thus the activation-energy, increases with increasing confining pressure.

"Deep-focus" earthquakes originate at depths of about 700 km. The confining pressure and the temperature corresponding to this depth have been estimated as about 250,000 bars and 2000° C. Plausible theories that may be replaced by many other equally probable hypothetical pictures cannot be considered as having satisfactorily explained anything. Here, however, by a process of elimination it can be shown that these earthquakes are probably the result of a temperature-pressure-phase change mechanism.

This mechanism will function if the material at a depth of 700 km can exist as either one of two forms A or B, B being denser, and the temperature is such that fluctuations in the thermal gradient can effect the transformation from one form to the other. Lowered isotherms then induce the change from A to B with accompanying collapse, and raised isotherms the change from B to A with expansion.

From a study of the Earth's past history we learn that such temperature-changes must have occurred. Moreover, certain periodicities may also be adduced and if these are used in conjunction with the above mechanism we have also a plausible explanation of crustal uplift and downwarping.

It seems rather unfortunate that the term "viscosity," which has a definite meaning, should have been loosely used in reference to flow in solids. "Pseudo-viscosity," a negative term, is hardly less objectionable. The derivative of unidirectional stress with respect to strain-rate has the dimensions (mass/length × time^2) or poises, but for fluids this coefficient is independent of stress and of time. For creep or flow in solids, however, the coefficient varies with both stress and stress-rate. It also varies with time except over that portion of the curve designated as the steady-state creep-rate. Such phenomena might better be expressed by a more general term such as "mobility" which would be given by the inverse of the above coefficient and expressed by the convenient unit reciprocal poise.

Instead of attempting to combine the elastic and plastic phenomena as by a term such as "elasticoviscous" it is important to distinguish between them. For rapidly applied, that is, high-frequency, loading and unloading, the material at 700-km depth is expected to behave as a very strong elastic substance according to the first mechanism mentioned above. For slowly applied stresses or loads existing for long periods of time the fundamental strength of the material, given by the relations of the second mechanism, must be very small. This is borne out by the estimated "mobility" of about 10^{-22} reciprocal poises for the small-load remnant of that resulting from removal of Pleistocene glaciers.

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PLASTODYNAMICS AS INDICATED BY GEOLOGIC STRUCTURE

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(The writer thanks the Geological Society of America for an allotment from the Penrose bequest to cover the cost of preparing and illustrating this paper.)

Plastodynamics is the dynamics of plastic deformation. The part of it here considered is that which rules the natural flow of solid rock, as revealed by rock-structure. When better understood, it may elucidate the fluid element of the slow deformation of solids, an element that seems inadequately described in systems of mechanics that treat solids as elastic or wholly solid, regardless of the velocity of deformation.

The realm of very slow deformation has been little studied, but in another paper, David T. Griggs will discuss the time- and stress-relations of plastodynamics as revealed by experiment. The present paper endeavors to show only the necessity for a new concept.

The diminishing rôle of elasticity

Its disappearance in slow deformation--Following Nadai [see 17 (1931) of "References" at end of paper] elasticity will be treated not as a property of rock, but as a feature of deformation. Within certain limits, it varies as the speed of deformation [Ewald, Pöschl, and Prandtl, 10 (1930)]. Reasons will be given for believing that, if the deformation be very slow, it may proceed without regard to elastic strain. Thus, with reference to very slow deformation, elasticity is thought to vanish, along with elastic strength and with all other features of solid deformation that depend upon elasticity of form. This disappearance of elasticity affects only a slow part of some deformation, but it is thought to rule all parts of very slow deformation, especially schistose gliding and pure folding, without breaks. It does not affect the reaction of the same solid to rapid disturbance, as in seismic waves, which may traverse a body of rock that is slowly flowing under a longer-lived, but independent and quite different set of forces. Nor does the disappearance of elasticity in the slow part of a deformation affect anything that occurs in the rapid part, such as fracturing, thrusting, etc. In very slow deformation probably only a viscous strength is concerned, even though the response of the same substance to faster action is elastic.

In Recent sands there are mica-flakes that are permanently bent against little pebbles or dented by sand-grains. The flakes do not resume their original shapes when freed from confinement. Strata bent by Recent faulting show no tendency to straighten out. Any original elastic strain has been lost by setting.

The small reversal of vertical displacement that followed earthquakes in New Zealand [C. F. Adams, 1 (1933)] and in Japan was completed within a few weeks. To the extent that this reversal was due to elastic relaxation, one may suspect that the life-period of the residual elastic strains amounted to no more than a few weeks. Afterward, only a subsequent stress could renew them. (We are not immediately concerned with elasticity of volume, which may have long duration.)

Plasticity of folding--In other cases, involving slower deformation, one may doubt that elasticity had much importance at any stage of the process. Thus, quite commonly the folds of a mountain range are not cracked along their length, even though the rocks are sharply bent. Where longitudinal faults occur, they generally do not follow the lines of sharpest bending, but cut the steeper limbs, which may be overturned. All fracturing may involve elasticity, but these longitudinal breaks are due to shearing, not to bending. There is nothing in the structure of the common type of folding that simulates the bending of a beam, as surely it would do, had the bending or slow part of the deformation been elastic. We have seen that elastic strain in rock disappears by setting at some unknown but appreciable rate. Obviously, if the application of stress does not create new elastic strain faster than the strain disappears, the whole deformation must be plastic. In such cases even the transmission of tectonic force need not be elastic, but more akin to liquid flow.

During folding the creep of strata over each other toward the fold-axes probably was finely diffused within the beds, for, in most cases, even of strong folding, one does not find striae running down the dip of the recognizable surfaces of beds. Other observations support the idea that slow rock-deformation is essentially plastic, and that it consists mainly of gliding along closely spaced, parallel planes. The position of these may be controlled by the constraining or guiding influence of more widely spaced, preexisting planes of weakness, as in the gliding parallel to stratification, just mentioned; or their position may be determined wholly by the stress-pattern, as in a monoclinal flexure, which is a zone of diffused gliding across the stratification.

Flow across monoclinal flexures--Dutton (1880) wrote: "Monoclinal folds are homologues of normal faults, from which they differ only in having their shearing distributed between two planes, instead of being concentrated along one plane." Here again, most of the gliding was too finely diffused through the rock to leave visible trace, at least in the monoclinal flexures that the writer has examined, mainly in Utah and Wyoming. Although a flexure is cut by numerous longitudinal joints, parallel to the normal fault that prolongs the effect of the flexure, few of the joints show any displacement along them, and the total of the visible displacements on all the joints is wholly inadequate to account for the monoclinal flexure. This set of joints is thought to have been formed late in the growth of the flexure, for otherwise, joints of their position would have become faults. The joints are thought to lie parallel to the more finely spaced, invisible planes along which most of the diffused gliding occurred. Some true bending may have been involved, inasmuch as the writer's measurements lack the precision required to determine whether, in crossing a monoclinal flexure, the thickness of a bed varies as the sine of its inclination to the glide-planes, as it should vary, if the flexure be due wholly to diffused

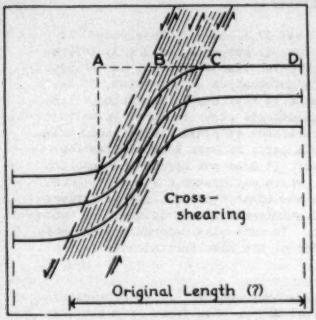

Fig. 1--Variation in thickness of bedding across a monoclinal flexure (the thinning shown in the sketch is less than that required by the sine-law)

gliding along the planes (see Fig. 1). Regardless of this uncertainty, Dutton's analysis of monoclinal flexing is quite acceptable, for the flexures have the same tectonic effect as the normal faults that they harmoniously prolong and overlap. They are the most satisfactory examples of the shallow flow of cold rock. The present writer believes that other examples are furnished by what he calls the "feeding" of displacement to faults, and its dissipation from them.

Cycles of deformation with increasing elasticity

Cycles in folding and faulting--In some fault-flexures, and in many fault-folds, both normal and reverse, there is evidence that folding began before faulting and before any jointing. Regional normal faulting so commonly follows folding that Stille [p. 236, 24 (1924)] calls it the "echo" of folding, after Argand's [2 (1920)] expression, contrecoup. More forcefully, it might be called "the last kick of a dying diastrophism." In the Gold Hill Mining District, Utah, Nolan [p. 65, 18 (1935)] distinguishes five "cycles" of deformation, each of which began with folding or thrust-faulting and ended with normal faulting.

In other words, during each cycle the deformation became more elastic. Thrust-faulting generally was preceded by considerable bending of the strata. In a fuller study the writer will show, further, that, within a single cycle, successive sets of normal faulting became increasingly elastic with less "drag" and other so-called "bending" of the rocks, with less-diffused "feeding" of displacement to the faults, and with progressively closer approach toward "block-movement."

Cycles in metamorphism--In the development of the schistosity of the northwestern flank of the Adirondack Mountains and of Dutchess County, New York, the first recognizable event was the formation of a group of structures, to be described later as beta-lineation, along what Gilluly calls the "tectonic strike." Subsequently, either in the same or in a later cycle of deformation, alpha-lineation was created, originally normal to the former, which, however, it rotated locally into far different position, probably through as much as 20° or 30°. The geographic trend of the alpha-lineation is the same as that of the striae on adjacent, sharply marked overthrust-faults that cut the planes of schistosity, generally at low angle. The overthrust-faulting, thus, appears to have been a late, more elastic phase of the cycle of deformation that produced the alpha-lineation, and, since faulting of any kind is less plastic than fine schistose gliding, the association of the overthrusts with the alpha-lineation suggests that the latter arose from a deformation that was less plastic than that which had produced the beta-lineation. However, too little is known to give much value to this tentative suggestion that, even in the development of schistosity, there may be a decrease in the plasticity of deformation. Moreover, the

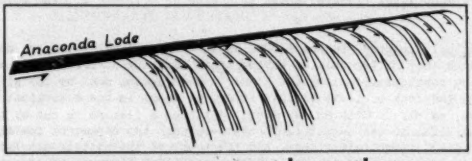

Fig. 2--Diagrammatic restoration of "horsetail"-veins at Butte, Montana (These are here treated as "distributaries" of an eastward displacement of the south wall of the Anaconda Lode; if that wall moved westward, all the arrows should have the barbs on their other ends, for, in that case, the "horsetail"-branches would have acted as "feeders" of displacement to the main tear-fault)

presence of alpha-lineation in flowing water, as along an ocean-current, to be described, proves that some of its manifestations do not require any elasticity. This may be true especially of the earlier, more plastic types of alpha-lineation, as will be discussed under that subject.

Logically, a cycle of deformation should include also an initial stage in which plasticity increases, but, in the available description of rock-structure, there is rarely a trace of this initial stage. The few instances of normal faulting before folding possibly may represent the end of an earlier cycle. The later growth of a structure can not be distinguished from the earlier, if it be of the same general type. The phase of anticlinal growth that in places occurred during the deposition of sediment seems quite like that which followed deposition, except in cases where the early movement produced broad arches, instead of narrow folds--an indication of greater elastic strength. A trace of this initial part of a cycle is furnished by the cross-fractures of the Jura Mountains, at least some of which are older than the folding.

Cycles in fault-veins--An interesting example of such an increase in plasticity during the early part of a complete cycle of deformation seems to be furnished by the present writer's interpretation of the systems of fault-veins in the Pachuca Silver District, Mexico, described by Wisser [25 (1936)]. Wisser regards the tear-faults that are followed by the north-south veins as coeval, antithetic mates of those followed by the west-northwest veins, but the evidence he presents seems better interpreted as indicating that the latter are slightly younger than the north-south set. This question will be more fully treated in another study. The tear-faults of the presumably older north-south set have very small displacement, and their wall-rocks have been little altered; while those of the west-northwest set have larger displacement, and their wall-rocks have been greatly altered. The deformation that produced the latter probably was the more plastic, as indicated by the presence of numerous mappable "feeders" of displacement, which curve southwestward from the west ends of the faults [see Wisser's Fig. 2]. The minerals in both sets of veins are essentially the same, and there is no apparent reason to think that the mineralizing solutions of one set were hotter than those of the other. More likely the walls of the younger or west-northwest fractures were subjected to a longer period of alteration by hot solutions, during which they became hotter and weaker than the walls of the north-south set. The local cycle was completed, in the usual way, by normal faulting.

As so interpreted, the course of tectonic events at Pachuca was exceptional. It was opposite to the otherwise comparable history of the veins at Butte, Montana [Sales, 19 (1914)], where an older or east-west set, the Anaconda Lode, had its original walls deeply destroyed by severe alteration and replacement, and cut by a multitude of small oranches that curve into the south wall of the Lode with a decidedly plastic pattern (see Fig. 2). These "horsetail" veins conceivably occupy either "feeders" of horizontal displacement to the original fracture of the Anaconda Lode or else "distributaries" of displacement from the latter, but the alteration of the wall-rock has been so great that no one can say whether there was any faulting along the fracture. In contrast, there was but slight alteration along a younger set of fault-veins that trends northwest, and the branching of which is rare and of more elastic type. The mineralization along the two sets is essentially the same, indicating that both belong to the same cycle of deformation and were formed doubtless during a late stage of the cooling of the granite batholith in which they occur. The history of the Butte veins differs from that of the Pachuca veins mainly in that it follows the normal course of a cycle--a progressively decreasing plasticity of deformation.

Cause of cycles--Nolan avoids speculation as to the cause of the cycles of deformation at Gold Hill. The examples of Butte and Pachuca suggest that in regions of this kind a period of decreasing plasticity may follow a softening of the rocks by igneous intrusions or by hot magmatic waters. The application of that explanation to the five cycles of Gold Hill seems weakened by the apparent lack of evidence that there were five corresponding periods of heating. Nor is there any evidence that magmas influenced the cycles of deformation in the Ruhr Basin of Germany and in the Belgian coal-fields. Moreover, in the immediate vicinity of the structures of eastern America, there was more igneous activity during the Triassic faulting than there was during the preceding, more plastic, Appalachian diastrophism. In such cases, the usual inference is that the whole crust was softened where depressed beneath a geosyncline and that it hardened after folding, as Stille believes. In many other cases, such as the increasing elasticity of successive phases of faulting in the Great Basin, some other explanation must be found.

Structural comparisons indicate clearly that a lowering of the pressure normal to the glide-planes decreases the plasticity of rock-deformation. An increase in the pressure normal to the glide-planes augments the friction along them, so adding to the drag-strain within the glide-sheets, until the latter may split into thinner sheets, ultimately subdividing even the finest cleavage. A reversal of this process, aided probably by cooling, may be seen by comparing

the folded rear or the cleaved root, if any, of a large thrust-fault, with its more elastic frontal section. The cleavage-zone parallel to a deep overthrust-fault would so scatter the gliding that it would weaken any seismic wave that the displacement could generate. Probably it is some cushioning effect of this kind that explains the lack of evidence that any known earthquake arose from a low-dipping overthrust. In the opinion of Henderson [13 (1933)], the Hawke's Bay Earthquake of 1931 was produced by slipping on a steep reverse fault, the only case of the kind that has been reported, but across a fault of this kind the normal pressure need not be high, especially since the deep hypothetical fault trends north-northeast, not far from the probable direction of recent major pressure of the region, as indicated by other fault-phenomena. Koch [14 (1933)] says that no appreciable tremors have been caused by the small overthrusting now active in Buena Vista Hills, California. As tectonic action rises into shallower rocks, the upward decrease in confining pressure doubtless abets the corresponding decrease in temperature in decreasing the plasticity of deformation. Large normal faults are not favored loci of dikes and veins, and there is no reason to think that any of them can descend deeply into the Earth before the pressure across them scatters their displacement among the many glide-planes of a monoclinal flexure, or other zone of disseminated movement. On the other hand, in rising toward more elastic zones, disseminated movements tend to coalesce.

Because of the pronounced effect of normal pressure in causing a wide distribution of shearing through the rock, the writer believes that the very deep earthquakes, recently discovered, must be generated on glide-surfaces so steep that the great weight of overlying rock has minimum frictional effect on a rapid horizontal movement. Vertical tear-faults are the most probable source. At great depths, the component of weight of overlying rock that would be exerted across any but a vertical glide-plane is so great that probably only the latter could tap deep magmas. From similar considerations, the writer infers that orthogonal joints, parallel to the direction of major pressure at the Earth's surface, and to the presumably identical direction of greatest plastodynamic force (flow-lines) of great depth, are the only joints that could tap the sima. All great dike-swarms of basic rock that have been described follow nearly parallel and nearly vertical paths along the probable direction of the major horizontal pressure of their period, that is, orthogonal joints. These relations mean that the cessation of a rather continuous horizontal pressure, such as may have prevailed during the more plastic phases of diastrophism, would be accompanied by a decrease in the plasticity of deformation.

The decrease in plasticity during the commonly detected part of a cycle somewhat resembles the metallurgical effect called "work-hardening," but the amount of working that the rock has undergone seems negligible in comparison with that in the cold-rolling of a metal. Since we do not know the sensitivity of rock to similar treatment, an experimental test might not be amiss. However, the previously mentioned effect of normal pressure in increasing the plasticity of deformation, apparently well established, may be inconsistent with the suggested application of "work-hardening" to the problem.

Finally, in so far as finely diffused gliding along many surfaces is "fed" concomitantly to a smaller number of surfaces, the gliding along each of the latter will go faster, as well as farther, than that along any of its then active, tributary surfaces, and greater velocity means less plasticity of deformation. Under the writer's opinion, a decrease in the number of glide-surfaces is the essential mechanism of decreasing plasticity of deformation, which makes the preceding statement superfluous; yet it again calls attention to the close interdependence of velocity, plasticity, and diffusion of gliding. Among these, cause and effect can not be discriminated.

In summary, the general decrease in plasticity during the commonly observed part of a cycle of deformation may be assigned to cooling, to decrease in confining pressure, and, perhaps, to work-hardening--a remote possibility. Other conditions being unchanged, any mechanism that promotes the concentration of fine gliding onto fewer surfaces would, by definition, decrease the plasticity of deformation of a given substance.

Plastic response may be slow and indefinitely continuous, while elastic response may tend toward quicker, spasmodic movement, after longer periods of idleness during which stress accumulates. The preceding remarks show that "plastodynamics" must account for various combinations of the two types of movement and especially for a progressive decrease in the relative plasticity of successive stages of the commonly observed part of a cycle of deformation.

Schistose structures and their analogues

The cleavage and especially the lineation of metamorphic rocks best display the liquid part of solid deformation. In schist and gneiss the three main elements of structure are: (1) Dy-

namic lamination; (2) alpha--lineation, along the direction of gliding; and (3) beta-lineation, along the tectonic strike and originally normal to the direction of gliding.

Dynamic lamination--Sheet-structure is the outstanding characteristic of metamorphic rocks, of igneous sills, of at least the marginal parts of large intrusions, and probably of all large bodies that flow slowly, whether solid, liquid, or gaseous. Planar schistosity, slaty cleavage, gneissic structure, flow-banding, stratus-clouds, etc., are merely different words for the products of one predominant process, namely, laminated flow.

A prime reason for the predominance of laminated flow is the constraint to flow that is exerted by floors and walls, and by the equivalent of these, such as thrust-faults, and, in some cases, bedding, and other preexisting planes of weakness, which can guide the flow best if they have suitable orientation with reference to the main force (the word "stress" is intentionally avoided). In magmatic flow the constraining influence of a wall is strongest at its surface, where the first flow-layer appears. Then, each successive glide-surface in the magma acts like a little subsidiary wall that guides the flow behind it and so determines the orientation of the next glide-surface inward. (The spacing of the glide-planes may depend on viscosity and velocity.) This process goes on, progressing farther into the magma, gradually smoothing the paths of gliding by greater departure from the irregularities of the wall and with increasingly wider spacing of the visible glide-surfaces, until the influence of the wall is no longer felt and the ever fainter lamination disappears. In large intrusions the sharper irregularities of the wall may lose command of the magmatic sheeting, also because the wall itself soon takes part in the movement and becomes sheeted with active glide-planes parallel to those that its constraints had created in the magma. In such cases, irregularities of the wall have little, if any, apparent effect on the position of the flow-surfaces, which follow only the general trend of the original wall and cut across the sharper deviations of the wall from its general course.

The position of planes of schistosity that cut stratification possibly may have been determined by thrust-faults that had been formed during the initial, less plastic part of the cycle of deformation. The writer has not seen any direct evidence of these hypothetical, initial structures, but thrust-faults characteristically are bordered by thick belts of cleavage or jointing parallel to them, and it seems evident that their constraint would guide any later, fine gliding that caused slaty structure and plane schistosity. Because of the weakness of the latter, it seems likely that their position was determined by some stronger, preexisting structure.

In metamorphic rocks a second fundamental cause of the predominance of laminated structure may be found in the geometric fact that gliding along parallel planes would not have to sunder or overcome as many of the automatically generated attachments or attractions between flow-units, as would any other type of pervading movement. In other words, gliding along parallel planes is the type of internal movement that consumes least energy. This application of the principle of least effort gives further support to the opinion that the plastic deformation also of cold rock is accomplished mainly by gliding along parallel planes.

The preceding paragraph applies to slow flow in solids and in liquids but not in gases, the molecules of which lack bondage. Yet the sheet-structure of smoothly flowing air, free from turbulence, is well demonstrated by the forms of stratus- and cirrus-clouds. These seem to glide with horizontal shear-layers of air, which are oriented probably by a far-transmitted constraint--the drag of the wind against the Earth's surface--more than by density-stratification. That a thin cloud-sheet is a shear-layer is proved by the positions of its two lineations with reference to its direction of gliding.

In large bodies of smoothly flowing water, parallel lamination has not been demonstrated, to the writer's knowledge, but its existence is highly probable because of its almost complete dominance of the flow of solid rock and of non-turbulent air--states of matter that lie on both sides of liquidity. Moreover, the writer finds it impossible to explain the high development of alpha-lineation along ocean-currents, unless these are divided also into laminar flow for, as expressed below, he regards alpha-lineation as a further subdivision of dynamic lamination. The top layer, which receives the strongest impulse from the wind, must shear over a layer beneath it, and so on, down to the deepest layer of the current. Possibly the top layer is thick enough to contain the orbits of molecules that accommodate wave-motion, an interference that would not affect deeper layers.

Alpha-lineation in rock--Under this term the writer includes a group of linear features that lie in the direction of gliding. The least plastic and youngest variety of alpha-lineation consists (1) of striae or little grooves on the surface of cleavage, which resemble the striations of a small overthrust-fault, of which there may be (2) a neighboring example that cuts the

cleavage at low angle and that is striated along the geographic trend of the other types of alpha-lineation. Approximately of the same late age as the preceding, there may be also (3) trains of communicated mica-flakes and, rarely, of other disrupted minerals strung in the same direction along the cleavage-planes of slate, schist, or gneiss.

(4) A more plastic and probably older kind of alpha-lineation consists of little, open folds of the plane-cleavage. These generally have nearly constant width and height and disproportionately great length--in places seemingly endless, so rarely does one find a termination. Alpha-folds generally are nearly symmetrical and, so far as the writer has observed, none is overturned. These characteristics help one to distinguish them from beta-folds, which are much the more common.

Where alpha folds cross beta-folds, both may be transformed into lines of little, elongate nodes, the former remaining straight while the beta-axes become appreciably sinuous. The only example of this phenomenon seen by the writer is in the mountain just south of the sea-beach, five km east of La Guayra, Venezuela.

Current explanations of the origin of alpha-folds may be questioned, for the axial planes of those studied by the writer are parallel to each other and seem to lie in steep zones of finely diffused, harmonic gliding of small total displacement across the planes of schistosity. (The geographic trend of the glide-zones observed was not far from that of the dip of the cleavage, but it happens that the writer has not yet examined any alpha-folds that trend more than 45° away from the direction of dip.) The line of gliding evidently made a small angle with the trace of the cleavage on the steep cross-planes, in one case about 15°, but necessarily large enough to let the faint gliding produce little shear-folds in the cleavage. The zones of slightly transverse gliding along lines somewhat diagonal to the cleavage, which seems to have created these alpha-folds, are thought to be composed of potential, orthogonal joints, the Querklüfte of Cloos, along the ac-planes of Sander. Since these may extend far and may cut the strongest, as well as the weakest rocks, including relatively rigid massifs, they may interrupt the uniformity of any constraint exerted by the latter. They must do so if, as the writer believes, they are produced by slow plastic shearing ratner than by tension.

It is evident also that, where the position of the main cleavage is determined by an external constraint that guided the main flow, such as the boundary of a more rigid body, or a thrust-fault, the cleavage can not have the orientation that it would have taken under greater freedom of movement. In the marble near Gouverneur, New York, this may be demonstrated by observing how the flow-surfaces gradually depart from parallelism to a more rigid wall. Within only one-fourth mile from the latter, the dynamic lamination swings away from parallelism with the wall toward the general tectonic lines of the region. The same phenomenon may be seen in schist and in the flow-planes of granite. A similar degree of freedom from the guiding constraint that controlled the position of the cleavage would be furnished by any shear-zones near alpha that made large angle with the cleavage. The writer believes that the most abundant, incipient cross-partings of this nature are the orthogonal planes of weakness (ac-planes), little zones of which give the rock along them a slight release from the external constraint to flow. In these orthogonal zones of minor shearing, the rock may have enough freedom from that constraint to move more nearly in the direction that it would have taken under a less impeded or more remotely hindered flow or that it would have taken from the main, regional, tectonic force alone. That force, with its greater independence from local hindrance to flow (lateral constraint), would compel the rock in the orthogonal zones of weakness to flow slightly across the planes of cleavage, bending the latter into little alpha-folds.

In all cases where alpha-lineation is well developed, as in some of the quarries of building stone near Philadelphia, the orthogonal joints parallel to this lineation have not the smooth, even surfaces that characterize joints of this kind in their more commonly recognized relation, which is nearly normal to a well-marked beta-lineation. The cause of this difference in behavior of joints that have the same tectonic orientation (ac) is not understood.

In a system of dynamics that treats solids as elastic regardless of the velocity of deformation, there can be no shearing along planes that are parallel to the direction of major pressure, such as these orthogonal or ac-planes. However, the presence of strong alpha-lineation in smoothly flowing water proves that a sheet of water advances unequally by shearing on surfaces (or along zones resolvable into glide-surfaces) that cut the sheet along the line of flow. In liquids there is no line of major pressure, but the direction of flow is that of the transmission of hydrodynamic force, which may have a similar effect in plastic deformation. The more plastic phases of alpha-lineation in metamorphic rock thus seem to express liquidity but, since they occur in a solid, they will be called "plastic" phenomena.

(5) The orientation of minerals along the direction of gliding is the most plastic and apparently the oldest manifestation of alpha-lineation. Most or all of it was produced during crystallization and recrystallization, when the planar schistosity arose and, therefore, long before the four other kinds of alpha-lineation had arisen. So interpreted, these varieties of alpha-lineation represent at least three successive stages of deformation or steps of progressively decreasing plasticity of deformation, as in the usual cycle.

The straightness of some slender minerals, such as the rutile-needles that trend northwest, in the alpha-direction normal to the general course of the Appalachian folds--as seen in the slates of Pennsylvania [Behre, 5 (1933)]--and the apparent scarcity of needles that depart far from this orientation tends, in this case, to minimize the probable importance of rotation, in the sense of end-for-end, and to increase the probability that a directed, original crystal growth had much to do with the orientation of the rutile.

In the talc-deposits of northern New York studied by James Gilluly and the writer, long slender needles of tremolite have the same geographic trend as the striae on small overthrust-faults, which the needles, however, cross at low angles, in most places, of about 5° to 15°. This description refers to the locally prevalent relation, in which the fault-striae have a large element of dip-slip. Probably it would be more generally correct to say that both the tremolite-needles and the fault-striae lie on Sander's ac-plane of deformation. They are undoubtedly two closely related features of alpha-lineation, both controlled by the thrust-movement. Close to some of the faults the plating of the talc becomes nearly parallel to them and, nence, is cut at nearly the same low angle by the needles of tremolite that project into the other wall of the fault. The talc probably was formed by the alteration of tremolite, which, therefore, is regarded as the older of the two minerals--a relation that seems to preclude any probability that the needles grew across a fault-surface after the faulting stopped. Apparently the talc, in gliding along a thrust-fault, must have flowed with great ease around the needles. The rather slender needles were not bent by the flow nor broken off at the fault-surface that they cross. Possibly the needles were rotated uniformly and without bending from positions more nearly parallel to a fault, for they transect the latter in such a way that, if one slip a finger along the direction of thrusting, the fault-surface feels very rough, almost pricking the skin. In two cases there was, perhaps, an opposite inclination of needles to the direction of fault-movement, as indicated mainly by drag-structure, but, in these places, we could not certainly determine the relative direction of the displacement. In one place tremolite-needles were seen to cross a little thrust-fault that has walls largely of marble. The evidence that talc and calcite flowed so easily around weak, slender needles, so that gliding along the thrust-plane did not shear them off nor even bend them, indicates the high plasticity of this pre-Cambrian thrust-faulting, which closely resembled liquid flow.

As described by Cloos and by Balk [4, 1937)], the flow-planes (dynamic laminae) of igneous bodies behave much like those of metamorphic rock, as do also the flow-lines (lineation). The only significant difference is that these authors report orthogonal joints (Querklüfte or cross-joints), not only nearly normal to what the present writer calls beta-lineation, where such joints belong, but apparently also normal to alpha-lineation, where decidedly they do not belong, under any extant theory of their origin. It seems unlikely that all the flow-lines in the igneous bodies studied by the Cloos school could represent only beta-lineation. Especially does the description by Cloos [7 (1927)] of the Drachenfels intrusive seem discordant with such theories. In this igneous plug, there are vertical flow-lines cut by horizontal joints. The magma evidently pushed upward along the flow-lines and horizontal joints normal to vertical flow-lines could neither be tensional, as required by the theory of Cloos, nor shear-joints, as inferred by the writer, unless they were formed by forces independent of the upward push of igneous material after that movement had ceased. In both igneous and metamorphic rocks, either of these two explanations of orthogonal joints requires that they must cut an undisplaced beta-lineation nearly at right-angles, and must lie parallel to alpha-lineation. Failure to recognize this relationship in the field may arise from the fact that, where they follow alpha-lineation, the joints of this set have much rougher surfaces than where they cut beta-lineation, making them more difficult to recognize as true orthogonal joints.

In the slates of Pennsylvania, Behre reports innumerable steep planes of weakness that strike northwest, that is, along the alpha tectonic direction of local Appalachian folding but which generally do not open into conspicuous joints, although they are most useful in trimming individual layers into roofing slate. The predominant lineation of the slate likewise follows the regional alpha-direction nearly normal to the axes of the major folds. In that area of slate, orthogonal joints are rarely seen although some are opened by quarry-blasting and more by the hammers of slate-trimmers.

Outcrops in which alpha-lineation is well developed, in Dutchess County, New York, reveal a few steep, rough joints along the lineation; while nearby outcrops in which beta-lineation is well developed reveal a larger number of much smoother joints that have the same tectonic trend as the former but which, in these outcrops, lie nearly normal to the beta-lineation, the position in which they are most commonly recognized.

Lineation in water--Alpha-lineation may be well developed along the line of flow of water. Balk [4, Pl. 22, Fig. 11 (1937)] reproduces a photograph of the feature by Nakamura, which displays long, narrow, open plications of the water-surface, or alpha-folds, that trend normal to the general crest-line of a breaking wave. The photograph shows belts of light, reflected from the water-surface and so distributed as to prove that they come from true plications of that surface. Balk's legend for the Figure says "The streaks of water and air particles are parallel to the forward motion of the water." Along the front of the rounded crest of the breaker, the structural height of some of the plications increases, and these project slightly ahead of neighboring parts of the wave-front. The phenomenon, therefore, is that of the unequal advance, along alpha, of narrow zones of differential flow. Not only did an individual flow-line advance farther than its neighbor on one side, but it also rose a bit higher than the latter, so helping to make an alpha-fold.

The writer believes, further, that if an underwater photograph could be taken, looking along the trend of the breaker, one would see other lines of débris and bubbles that lie along low-dipping surfaces of laminar flow. It seems obligatory to think that any difference in the unidirectional, forward advance of parts of a straight-moving body, whether solid, liquid, or gaseous, must be accommodated by plane shear-zones, or surfaces of gliding, that separate the unequally moving parts. In Nakamura's photograph, the way in which the structural height of alpha-folds increases along the frontal slope of a wave-crest suggests that the cross-planes of gliding that made an alpha-fold were vertical. The flow of the water thus is thought to be divided into pencils by two intersecting sets of glide-planes. The pencils glide over and alongside each other, moving mainly along their length, but the vertical planes along their sides (ac-planes) give them a small, additional freedom of movement, allowing a component of upward and downward displacement that produces alpha-plications of the water-surface.

It is unusual to find lineation so well developed in water that has the high velocity of that in breakers. Turbulence generally masks the phenomenon in conduits as small and as fast as rivers and eddies disturb it even in the parts of an ocean-current that touch a shore. As noted by Balk, however, it is indicated by the alignment of logs along the current of a river.

Probably the finest display of the phenomenon is that in an ocean-stream, as viewed from an airplane. In flying from Barranquilla to La Guayra and looking down on the Caribbean Current that flows westward with the trade-wind off the northern coast of South America, one observes that the sea is etched with fine, nearly straight, parallel, east-west lines. Closer study from a small boat later showed the writer that the lines are due largely to very sparse vegetation floating on the surface and to similar débris that drifts at various depths in the water, which is unusually clear. Normal to these fine, seemingly endless, little alpha-lines are comparatively short, white, broken north-south streaks, that mark the position of white-capped waves, each slightly concave in plan toward the east wind. Waves are the only analogues of beta-lineation in water that the writer has recognized.

Just as the origin of dynamic lamination or flow-layers may be assigned to the drag-effect or constraint of a distant floor or roof, so also may each of these flat layers be subdivided into alpha-lineation by a lateral constraint that prevents one side of a glide-sheet from advancing as fast as more distant parts of the sheet. The dragging influence of the north shore of South America upon the Current is such lateral constraint exerted along the south side of the west-flowing Caribbean stream. The effect probably is to break the horizontal flow-layers into alpha-filaments or pencils, which should tend toward rectangular cross-section.

Lineation in clouds--As in rock, most of the lineation in clouds is of the beta-type and originally was normal to the glide-lines on the shear-planes. (Lineation is best seen in high, sparce clouds free from turbulence, especially in thin stratus- and cirrus-forms. It should be studied only at angles of elevation that exceed 45° above the horizon, preferably near the zenith. Some features are most safely studied when the clouds are lighted either by the Sun or by the Moon shining from just beneath the horizon so as to cast more light on an upper cloud than on a lower one and thus prevent the observer from confusing the layers. If stars can not be used as points of reference for the cloud-drift, the observer should stand or lie beneath some other fixed guide, such as the cross-arm and wires of a telephone-pole.) These are horizontal air-layers at the cloud-level. The phenomena differ from those in rock mainly in the rapidity

with which beta-lineation in clouds may be rotated by shearing along alpha-surfaces, which are steep enough to cut a cloud-layer sharply. In cloud-action also the amount of this rotation is much greater, for it may bend part of a beta-roll or beta-strip through a complete right-angle, that is, until the bent part (and in some cases the whole beta-lineament) becomes parallel to the glide-lines and so joins the alpha-lineation, from which it never can depart unless the direction of gliding changes (see Fig. 3).

Only alpha-lineation remains nearly straight and parallel in all parts of a cloud-group while beta-lineation takes different forms, wave-like or sinuous, in places tufted at the ends or gently divergent, etc., and takes positions variously inclined to the wind in which the cloud rides. Although alpha-lineation strictly follows the glide-lines of an air-layer, it may depart as much as 15° from the direction of drift of its clouds with reference to the ground-surface. (An example may explain this. If one air-sheet moves northward and the contiguous layer moves north 30° east at the same velocity (possibly an extreme divergence for a short difference in height), the line of shearing between the two layers would trend north 15° east.) Yet, so far as the writer has observed, alpha-lineation always maintains the same geographic trend as far as a cloud can be observed to drift across the sky, regardless of the amount of rotation, bending, and other alteration of the beta-strips that it crosses. This behavior of the air again resembles that of rock, in which it is only the beta-lineation that is rotated far (in some cases 20°) from its original position, normal to the glide-lines, while the alpha-lineation and the orthogonal joints constantly follow the glide-lines from which apparently they can not depart.

Beta-lineation--This consists of the axes of small folds and minerals that, when formed, are oriented normal to the glide-lines on a cleavage plane but which later gliding along transverse planes may swing through at least 20° from normality to the glide-lines. If large folds be included in the group, as those of the Jura Mountains, their trends suggest that this swing may be much greater, but the mechanics of such ranges can not be understood until their glide-lines, orthogonal joints, veins, dikes, etc., have been mapped. Alpha-lineation marks an inequality in the advance of parts of a shear-layer, while beta-lineation marks an original equality of advance of the layer, as though toward an even front.

Although beta-lineation is the most abundant and, in some respects, the most important linear element of metamorphic rock and of large igneous bodies, its features seem to add little to the present thesis beyond those already mentioned in their relation to alpha-lineation.

If, as is generally thought, the little beta-folds on a shear-surface are created normal to the glide-lines on that surface, they are not necessarily parallel to any stratification that the cleavage crosses, although they may happen to have that position. Hence, it is doubtful that they should be used in trying to unravel the stratigraphy of metamorphic rocks. Certainly, alpha-lineation must not be used for that purpose. The confusion of the two, heretofore, has led to some unwarranted conclusions.

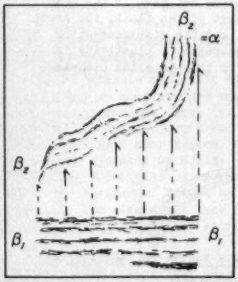

Fig. 3--Rotation of beta-lineation in a high cloud, from its original position, into final parallelism with line of gliding (alpha), which is shown by arrows with single barbs

The "feeding" of displacement to faults and its "dissipation"

Only some high lights from another study will be abstracted here, with emphasis on those that most pertain to the liquid phase (plasticity) of the deformation of "solid" rock.

"Feeding" of dip-slip to faults--Thrusting, generally of overthrust-type, characterizes a large part of the displacement along many of the planes of schistosity and other dynamic lamination, and along the surfaces of folded beds, that have been studied by the writer. Koch [14 (1933)] describes a little, active thrust-fault in the Buena Vista Hills, California, which is a clear, simple example of the way in which small gliding along the dip of many beds is being concentrated today upon a single plane of thrusting. From the description in Koch's text, the present writer draws Figure 4 to illustrate diagrammatically the general nature of the process for which Koch presents good evidence.

In the northern part of the area that is appreciably affected by the thrusting, the casing of oil-wells is gently bent through a thick zone, as illustrated by the right-hand well of Figure 4. Koch interprets this as a zone of gliding, the amount of which is

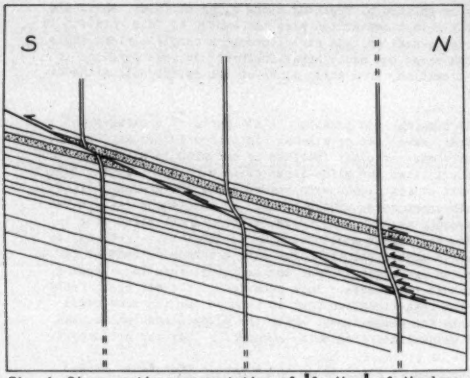

Fig. 4--Diagrammatic representation of "feeding" of displacement to a thrust-fault, that is indicated by Koch's description of a small one that is now bending and breaking the steel-casing of wells in the Buena Vista Hills Oil-Field, California

very small along each of a large number of bedding-planes. Farther south, the originally vertical steel-pipes are more acutely bent across a narrower zone and, finally, the pipe of the most southerly wells affected is sharply sheared off, as indicated by the well sketched at the left. Koch estimates that the thrust-faulting in this southern part of the area proceeds at the rate of about 1-1/2 inches per year. Where the displacement is finely distributed among the many bedding planes of a thick body of strata, as at the right of Figure 4, its velocity along any individual bed must be very small, doubtless placing that part of the process in the realm of high plasticity.

Regardless of the origin of a fracture, any "feeding" of displacement to it ultimately must be a plastic process, which may occur far from the part of the fault along which there is more rigid action, as where there is in any semblance to "block-movement." Toward the latter part of a fault, the plasticity of deformation decreases, as indicated, for example, by a decrease in the amount of drag-bending, or by a change in the sense of inclination of branches or other fractures with reference to the relative direction of gliding, or by less curvature of the branches, or by some other index of relative plasticity.

From the writer's point of view, the degree of plasticity of deformation depends mainly on the fineness of the spacing of the glide-planes--rather than on the flexibility of the glide-sheets--or of the theoretical, ultimate glide-units. The thinnest of these units is that of a layer of atoms in a crystal-lattice. He believes that all folds and the displacement on most faults, except the tensional varieties, arose primarily from diffused, plastic gliding.

The application of some of these ideas to a complete, large overthrust-fault is illustrated by Figure 5, in which A shows the main "feeders" of displacement in the highly plastic root-zone, which is strongly convex toward the more mobile side--a type of curvature not seen in the fractures of elastic deformation. Near B, in the less plastic, central part of the fault, the fault straightens, possibly with gentle, open rolls across the glide-lines, and the displacement is concentrated on fewer surfaces. Finally, in the frontal zone, C, a decrease in plasticity is indicated by the relative sharpness of the breaks, along which there is less pa allel cleavage,

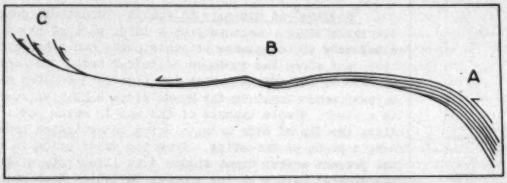

Fig. 5--Main theoretical parts of a complete, large overthrust-fault: A, the highly plastic root-zone, showing some of visible, schistose "feeders" of displacement; B, the central trunk-zone of more concentrated displacement; C, the frontal zone of "distributaries" of displacement (Plasticity of deformation decreases from A to C; all the curves may be original)

and, perhaps, by the sense of curvature of the branches, concave toward the more mobile side. These branches are the visible or coarse type of "distributaries" of displacement from the main fault. Thrust-faulting, as a whole, seems too plastic to generate large earthquakes, except possibly in the steep variety commonly called "reverse-faulting." In the case figured, even the frontal branches, C, have what the writer calls the "plastic" sense of inclination to the main fault, seen also in imbricate faults (Schuppenstruktur), and which is opposite to the sense of inclination of his "elastic" type of branching, seen in the Fiederspalten of Hans Cloos, and described as "feather-joints" by Ernst Cloos [6 (1932)].

The problem of "feeding" dip-slip displacement to upthrust normal faults and the spasmodic elastic updrive of the foot-walls of the latter involve matters that lie outside the scope of this paper. As in all other "feeding" of displacement, the process originates in diffused, invisible gliding which "feeds" displacement to the main fault--in many cases by the partial intermediation of lesser concentrations of the movement along "feeding" joints and confluent branch-faults.

To the extent to which the movements on the many "feeders" are concomitant, as they join one greater movement on a single surface, the rate of slipping along the latter would be the sum of the velocities along the individual simultaneously active "feeders." This increase in the velocity of gliding, as the "feeding" movements coalesce into the main one, would cause a corresponding decrease in the plasticity of the main movement. Other causes may combine with this to give elasticity ultimately a major part in the operation at some point remove from the root-zone of the fault. This and other features of normal faulting will be treated elsewhere.

The feeding of strike-slip to faults--Variations in the amount of horizontal displacement that occur along the glide-line of a steep tear-fault may be studied for long distances across the country because, as a rule, the glide-line lies not far from the general elevation of the ground-surface. For this reason, our knowledge of the "feeding" of strike-slip to tear-faults is much greater than that of the "feeding" of dip-slip to faults of other kind.

The amount of strike-slip along some tear-faults increases from almost nothing, near their ends, to a maximum along a generally subcentral part of their length. The diagonal cross-faults of the Jura Mountains furnish many examples. Of this nature is the distribution of horizontal displacement also along the San Andreas Rift, that occurred during the San Francisco Earthquake of 1906. The phenomenon requires a horizontal flow of additional rock into the body of one or both walls of a fault, "feeding" displacement to it; or, in some cases, it may require the opposite, a subtraction of rock from another part of a wall, by a plastic dissipation of displacement. At least one of the two alternatives is required wherever the amount of slip changes along the glide-line of any fault.

The sympathetic branches of a tear-fault that join it at angles that could permit the transfer of their displacement to the main fault all diverge from the latter so as to trend more closely to the "direction of major, horizontal pressure." Where the branches have visible, sympathetic sub-brancnes, the latter are seen to lie still closer to the line of pressure, with which, however, they make an appreciable angle. Obviously, the next finer order of gliding, along the hypothetical, invisible, diffused "feeders of displacement," must approach yet closer to the trend of major horizontal pressure. Otherwise, they could not "feed" strike-slip displacement to the sub-branches.

Is it possible that this approach of the invisible "feeders" toward the direction of major pressure may be complete and that the "feeding" surfaces actually are orthogonal joints that lie along that direction? When the writer first found a suggestion of this close relationship between the orthogonal joints and the small, nearly east-west tear-faults of the Coast Range of Oregon, best seen near Eugene, he disregarded it as absurd, for his thinking was then ruled by the classic dynamics of solids. He did not then suspect that it may be erroneous to apply the established principles of solid deformation to processes as slow as plastic, geologic deformation. The horizontal striae on the nearly east-west orthogonal joints near Eugene, or along the members of the dike-swarm that follow these joints, were thought to indicate a shift in the direction of horizontal compression, perhaps long after the formation of the joints.

The "feeding" of strike-slip to Jura cross-faults--Not until he had compared the position of little tear-faults that cross the folds of the Jura Mountains did the writer become convinced that it is necessary to postulate gliding along orthogonal planes in order to explain the "feeding" of horizontal displacement to the faults. The larger of these faults of the Jura make angles of 20° to 30° with the direction of gliding--assuming that this direction was normal to the present trend of the fold-axes--but, if one assumes that the northeastern part of each fold-axis was rotated northwestward by the cross-gliding, the original angle would be somewhat less

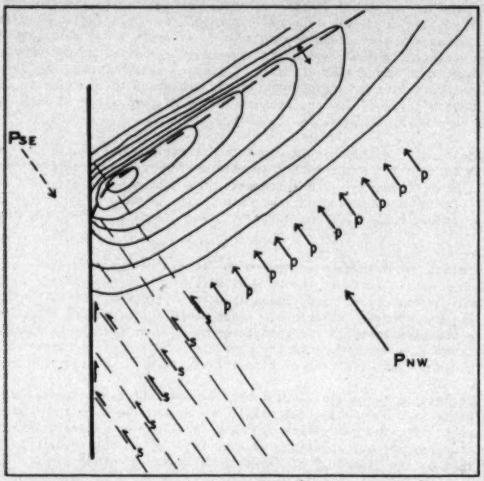

Fig. 6--Diagrammatic map to illustrate "wing-dam-effect" of a Jura cross-fault, in concentrating northwestward flow (P and s) of the strata along its eastern side, where flow made an anticline that has no offset continuation beyond fault, the floor also "fed" northward displacement to east wall of fault

than these figures. The eastern sides of all the large faults were displaced northward, a feature that Heim [12 (1919)] assigned to a concentration of northwestward push against the northerly trending faults. Although this statement may be correct, the only certain fact concerning the matter is that, along the eastern sides of the large, diagonal cross-faults of the Juras, there was a greater flow of rock toward the northwest, which caused the anticlines to grow much larger than those west of each fault. The cross-faults, undoubtedly, are older than most of the folding, as stated by Heim, and at least a few of them are older than the entire growth of a few, large anticlines that rise in their eastern walls but of which there are no offset segments west of the faults. The probable mechanism of the latter type (which should not differ from that of the former) is illustrated diagrammatically by Figure 6.

These large faults and folds alone do not suffice to locate the direction of gliding on the bedding, which, however, can be more closely approximated by comparing the positions of the large number of smaller tear-faults that are shown on detailed maps of the Jura Mountains. All faults that are inclined to the fold-axes in the same sense as that of Figure 6 have northward displacement of their east walls, and the smaller number that have opposite sense of inclination to the axes have northward displacement of their west walls. The trend of some of both classes of these smaller faults is more than 80° from that of the fold-axes, or less than 10° from the probable direction of gliding. Orthogonal joints in about this direction are reported by Schwinner [21 1928)], and since there are no other persistent sets of joints near that direction, it seems probable that the diffused lateral shearing that accommodated a greater northward movement of the more easterly rock must have occurred along the orthogonal planes of weakness, as along S in Figure 6. The direction of these ac-joints may be expected to indicate the direction of northwestward flow much more accurately than does a normal to the trend of the folds, for shearing of this type would slightly change the trend of the fold-axes without shifting that of the orthogonal planes.

The "feeding" of displacement in experiments with softened clay--The ideas here expressed seem to accord with the behavior of wet clay, in experiments by Hans Cloos, as revealed by his photographs [8, Figs. 7-10 (1931)]. These show a large number of closely spaced, steep, little

fault-scarps that run across the anticlinal axes at right-angle, being thus small, orthogonal faults. Cloos assigns them to tension normal to the elongation from compression, a process that could not operate across nearby parts of a body that had already been broken normal to the tension, which would then merely widen the preexisting break, rather than make a new one. If two, tensional breaks managed to form, certainly no extraneous tension could affect the material between them and, after the creation of several orthogonal breaks, tension could widen these only to the extent, if any, that it could be generated elastically within the intervening, vertical plates, as a by-product of compression along the plates, or else by the drag of an underlying flow, normal to the bottom of the plates, which would crack them in that direction, only if there were planes of weakness along it. As further indicated below, neither process seems capable of producing the observed orthogonal breaks, nor their subsequent widening into crevices.

Tension, as an elastic side-effect of compression, would be limited to the amount, if any, that could be generated within each vertical plate by horizontal compression along the plate, and this could not account for the widening of crevices. Permanent, lateral elongation is a plastic phenomenon, opposed by elasticity, which, under this common condition, would increase the lateral pressure, and not generate lateral tension, except possibly from the temporary part of elongations that have the unnaturally high velocity of those in the laboratory. If pressure along one of the orthogonal plates could possibly thin the plate in any way, as by an elastically made tension across it, it would be absurd to say that the compression could at the same time elongate the whole body normal to similar plates that compose it. Nor could it split an old plate, no matter how wide. The gaping of such breaks into crevices is no proof that they began as tensional fractures.

Cloos avoids the preceding paradox by assuming that the supposed, lateral tension is not generated elastically, but is a drag-effect of an underlying flow at the bottom of the orthogonal breaks. The present writer will extend his theory into its apparent implications. Although the surface of the clay was constantly sprinkled with water, the top layer may have been the first to break, possibly because the weight of clay may make deeper layers flow more easily and faster, and so drag apart a stiffer layer that rests upon that flow. The flow is being pushed, not pulled laterally, by the diversion of the primary flow of shortening along the direction of compression, into a secondary flow of elongation normal thereto. Within the flow itself there is only compression in all directions, tension in none. It is conceivable that an underlying lateral flow, normal to compression, could pull apart a layer that had been lifted on an anticline, a position in which the top layer would receive a minimum amount of the horizontal compression across the axis. Anticlines, in fact, are favored loci of orthogonal joints, which, however, also cross synclines, though in smaller number. Should an orthogonal break start in a surface-layer, because of the lateral flow of the next, underlying layer, the break would be propagated downward across successive layers, as they in turn stopped flowing, because of stiffening, or of decrease in the compression across them. Meanwhile, the crevice-walls in the upper layers, in which bodily elongation had ceased, would drift farther apart and the crevices would widen upward. Cloos reports that some orthogonal crevices gape upward, but there is no similar tendency in natural joints of this orientation. Further doubt arises from the smoothness and the straightness of orthogonal joints, characteristics that are opposite to those of typical fracture from tension. Even if drag from underlying flow could explain the formation of orthogonal joints in soft clay, and in magma, it would seem a strain on the theory to apply it to the orthogonal joints that are followed by basaltic dike-swarms, probably across the entire crust, for they are thought to tap the sima.

The Cloos theory of orthogonal joints is opposed also for another reason. In his experiments, the clay rested on a rigid base, into which one or both sides of a little fault-block could not descend. His tensional theory, therefore, requires greatest vertical thinning of the clay under each narrow little graben, and along the downthrow-side of each tilted block. This involves the apparent inconsistency of saying that, along the direction of maximum horizontal compression, a lateral tension or flow, derived from the compression, could thin the clay, along these orthogonal strips of downthrow, more than the direct compression thickened the clay upward, against no resistance but its weight.

The initial formation of orthogonal partings in material as nearly fluid as this soft, watered clay, seems to conform better with the theory of alpha-lineation in rock, water, and air, here under development, according to which there was small shearing or differential flow along orthogonal planes. This process would first create a great number of incipient, monoclinal flexures, resembling in principle the microscopic flexures in slate that Dale and Eckel [10-A (1906)] photograph as the initial expression of a younger cleavage across an older one. The zones of invisible shearing that made the monoclinal flexures number more than 500 per centimeter, and are separated by wider zones of no disturbance, in which the corresponding parts of mica-flakes

remain parallel to the older cleavage. Fracture of any coarse variety, such as jointing, selects but one out of many thousand of these finely spaced, potential partings.

Combining these indications, the writer explains the orthogonal scarps of the experiments of Cloos by inferring that the clay is cut by a large number of closely spaced, microscopic zones of steep orthogonal planes, along each of which there was horizontal gliding of exceedingly small displacement, which tended, at first, to make only faint, microscopic, monoclinal flexures along the zones. A selected few of the glide-zones became orthogonal breaks, along which there was greater horizontal gliding. Surficial scarps rose on the sides of these selected breaks that were the seat of greatest horizontal advance and vertical thickening of the clay. Greater thickening of clay along one side of an orthogonal break would create an upthrust, normal fault, with alpha-trend. This would have a considerable element of strike-slip, especially down the flanks of an anticline, toward the crest of which dip-slip would predominate, a relation seen also in the distribution of striae along some of the cross-faults of the Elk Basin anticline, northern Wyoming. As the deformation became more elastic, the steep, orthogonal plates would get stronger, and the horizontal pressure along them would tend to warp some of them in different degree, so as to widen parts of the intervening orthogonal joints into open crevices.

In some of the experiments of Cloos, the orthogonal fractures meet one or more, larger fault-scarps at angles of about 20° to 30°, which is close to the apparent position of the main, diagonal cross-faults of the Jura Mountains. It seems inevitable that a surface of this diagonal inclination would gather and deflect the flow of clay that impinged against it from orthogonal paths. The invisible, orthogonal flow is thought to have been lineated by the interaction of dual constraints, the vertical, orthogonal planes, and the bedding, if any, in the clay. In the absence of bedding of suitably low dip, some experiments by Kuenen [15-A (1908)] indicate that the function of these in permitting creep up the limbs of an anticline is satisfied by the formation of equivalent, little thrust-faults visible only near the sharper bends, but not improbably present as invisible glide-surfaces throughout the folding clay. In the experiments of Cloos, the steep, orthogonal glide-planes would "feed" strike-slip to one side of the diagonal fault that they meet and the low-dipping glide-planes would "feed" an upward element of displacement (dip-slip), the two processes combining, not only to lineate the flow, but also to make the diagonal scarp much higher than any along the orthogonal breaks.

"Ebb-and-flow" structure

By the term "ebb-and-flow" structure the writer designates a highly plastic type of shear-fold in which the shearing on opposite limbs of each fold has opposite sense, as though there had been a to-and-fro movement through the rock by alternating groups of parallel glide-sheets. The writer has observed the structure only where a well-developed, younger cleavage crosses an older one at high angle. In such places, however, it is common. Balk [3, Figs. 15-18 (1936)] made accurate drawings of rather extreme, or strongly sheared, examples of "ebb-and-flow" structure, as seen on polished rock-faces cut normal to the axes of the shear-folds approximately along their glide-lines. In these, as in the simplified representation of Figure 7, one observes nearly equidistant surfaces of greater gliding that make the flanks of the folds and along which there was greater crystallization of new minerals. The drag-bending along these surfaces of maximum gliding, as well as actual offsets along them, show that alternating members of the major, dynamic sheets generally moved in relatively opposite directions, whence the term "ebb-and-flow." The drag-bending indicates, further, that each of the well-marked sheets is subdivided into innumerable, much thinner, invisible glide-sheets, which are the real basis of the younger or "false" cleavage. That the severely deformed examples sketched by Balk represent deformation of very high plasticity is indicated by the great rock-alteration and recrystallization that occurred along the younger glide-surfaces of greatest displacement. (This exemplifies also what the writer regards as a "shear-control" of the solutions involved in metamorphism and of the magmas that enter most lit-par-lit structure, as is indicated especially where a tiny, pegmatitic sill departs locally at low angle from the cleavage but remains parallel to other little sills and minor glide-surfaces).

That two periods of deformation are represented by the younger or cross-shearing is improbable, because of the unlikelihood that the more active, younger shear-planes, say, B, which have one sense of shearing, would nearly always cut rather close to the middle of the older shear-sheets instead of following the previously prepared paths of maximum gliding in the opposite sense, such as A. New gliding probably would go back along the old surface represented by A instead of breaking through stronger material along a central part of a major, older glide-sheet. If any reason could be found why the more active planes of new gliding should break along that strange, median position, the other main details of the structure logically might be expected, except the still unexplained tendency toward symmetry that characterizes most shear-folds. Balk's drawings [3, Figs. 15, 16 (1936)] indicate that, commonly, there is approximate equality between opposite-facing folds (like tilted anticlines and synclines) in adjacent glide-sheets.

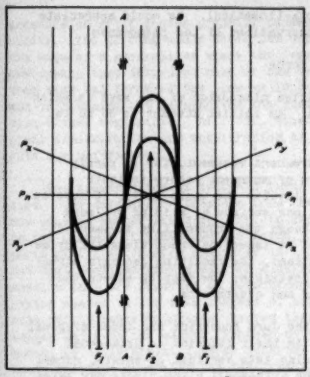

Fig. 7--Tentative analysis of "ebb-and-flow" shearing [A, B, etc., are the glide-lines (alpha-lineation) of planes of younger shearing across older cleavage, which it folded; major pressure directed along any line, P_x, that is inclined to one side of the normal (P_n) to glide-planes, could produce shearing in sense of A, but not in that of B; likewise, pressure along P_y (which is any line in the section, that lies on other side of P_n), could produce shearing like B, but not like A; for this purpose, the normal direction, along P_n, and the parallel direction, along A or B, also are forbidden positions of major pressure, under the dynamics of solids, under which, therefore, there is no direction of major pressure that could have produced a structure that undoubtedly exists. The phenomenon seems hydrodynamic, but will be called "plasto-dynamic."]

The phenomenon, though less pronounced, seems akin to that of the distribution of shearing with rhythmic spacing and harmonic amplitudes (glide-lengths) that seems required by many shear-folds. In other forms, the mystery has been sensed by Fujiwhara [11 (1921)].

If it can be so oriented, there is a possibility that the internal structure of a glide-sheet that lies normal to major pressure may be such that the plastic shortening of material along the line of compression is an internal flow that tends to swerve toward one side, which so determines the direction of slipping of the near wall of the first glide-plane that the internal flow meets; and that this tendency can proceed across only a limited amount of rock, measured normal to the main shear-planes, when the flow must swerve the other way, so reversing its sense, and "feeding" displacement of opposite sense to the next major glide-plane. One objection to this complicated suggestion is that Balk found that the major shear-surfaces in question furnished the principal passages for the entry of solutions, which greatly modified the rock close to them. It is evident that a major pressure normal to the shear-planes would tend to close them, and to make it easier for solutions to follow partings of other orientation.

Although one critic calls "ebb-and-flow" structure a "tectonic headache," it may be fitted tentatively into the scheme of this study somewhat as follows. The glide-planes, A, B, etc., of Figure 7 may have started as orthogonal breaks parallel to the major pressure of an earlier, more elastic phase of the deformation. After the action became highly plastic, the distribution of pressures would be almost hydrostatic, except that hydrodynamic force would be exerted along the lines of flow, A, B, etc., normal to which there would be faint, constraining forces that guided the flow along the shear-planes and lines. In other words, the postulated conditions were those of a flowing liquid, even though they occurred in rock that would behave as an elastic solid in its response to rapid disturbance. Since the force-system of the slow deformation could not have been that of a solid, as shown by Figure 7, it must have been that of a viscous liquid or, let us say, "plastodynamic."

"Ptygmatic" folding--A fair imitation of "ptygmatic" folding was achieved in an experiment by Kuenen [15, Fig. 6 (1938)] in which compression of viscous material caused subequal flow in two directions normal to the compression. In the center of the soft, deforming body and along the line of compression was placed a somewhat stiffer layer. The resultant, lateral wriggling of the latter had the irregularity and general appearance of some (natural) "ptygmatic" folding, and so differed fundamentally from "ebb-and-flow" structure, for it lacked an essential characteristic of the latter, namely, axial planes of shear-folding that are parallel to each other and to the well-marked, parallel planes of the cross-gliding that created the "ebb-and-flow" structure.

The term "ptygmatic" fold (literally, "fold-like" fold) is objectionable, not only for its redundancy but also for its omnibus-usage to include nearly any kind of complex plication or pseudo-plication in injected veins or dikelets. Kuenen reproduces figures from several authors that seem to represent far-different things, such as "ebb-and-flow" structure and other kinds of shear-folding, overturned folds, and a few examples that may be original plutonic structures that were injected with convolute form, and which, therefore, may be called "convolute injections" rather than folds. From a single, inadequate observation, the writer suspects that a convolute injection of pegmatite may enter the local rock along strong alpha-lineation. If so, in any cross-section parallel to alpha, the injected vein should be nearly straight, although

highly convolute in sections that cross the glide-lines (alpha-lineation). He would appreciate a test of this idea by any one who can make more numerous observations of the phenomenon.

The transmission of tectonic force

Although important, the writer is not aware of any detailed discussion of the ways in which tectonic force is transmitted through the crust of the Earth. An initial attempt to do so is, therefore, weakened by lack of background.

Any effective transmission of tectonic force must be permanent movement, for in purely elastic impulses, as in seismic waves, the component elements of movement return to their original positions. Since the transmitting movement can not involve the whole Earth, it must be separated from the uninvolved part of the latter by at least one surface of gliding or, more likely, by many glide-planes, that is, by a shear-zone. Although the transmitting movement itself may advance with so close an approach to uniformity that it leaves no trace along its prime position (the direction of major pressure in elastic deformation), the resulting geologic structure suggests that the transmission itself was divided into invisible, low-dipping sheets that advanced unequally over each other, to be diverted into folds and overthrusts.

Other structures, such as the diagonal cross-faults of the Jura Mountains and those diagonal to the folds that Cloos produced in soft, wet clay, suggest, in their relation to orthogonal joints, that the transmission of tectonic force was divided also into vertical ac-sheets, normal to the original trend of the fold-axes. A selected few of the orthogonal glide-planes may later be rendered visible as joints, through greater shearing along them or by tension across them, after the deformation becomes more elastic. The position of a still smaller number may be revealed by dikes or veins along them.

Under this theory, the direction of major pressure was initiated and was long continued as the direction of a primary, plastic flow, from which, under suitable conditions, elastic stress could arise, only to finally disappear through plastic adjustment or "setting." This would mean that the primary part of the transmission of tectonic force was plastic and only a secondary part elastic, with gradual change in the relative importance of these parts.

As presented by Andrew Leith [16 (1937)], the theory of the strain-ellipsoid is an explanation of the distribution of homogeneous, elastic strain that immediately precedes deformation. Since an elastic strain is short-lived and a long time is required to complete a large rock-structure, Leith's statement requires the further assumption that the elastic strain is not continuous but intermittent, each period of elastic strain being followed by one of adjustment to it. Inasmuch as any bend or fracture destroys the homogeneity of deformation, only the first impulse of elastic stress could be perfectly homogeneous--an ideal that might not apply even to the first impulse. The initial impulse could have carried little energy in comparison with that required to make the whole structure. Under that theory, a repetition of stress-impulses seems required also by the probability that rock can not store an amount of elastic strain adequate to produce a large fold--an amount that, more likely, would produce only fracturing. It would better accord with the Leith theory to assume that the elastic strain was renewed repeatedly by small, frequent impulses, so as to give at least a false effect of continuity in the resulting plastic deformation.

The general assumption that the prime transmission of tectonic force necessarily is elastic may have arisen from the fact that current ideas of the mechanics of deformation are based almost wholly on experiment in the laboratory on small blocks, in which the velocity of deformation necessarily is of higher order than that in natural diastrophism. The gliding of a mile of rock at the rate of 1-1/2 inches per year on the now active, overthrust-fault at Buena Vista Hills [Koch, 14 (1933)] reveals an order of velocity that, with reference to mass, will be hard to approach by the slowest work in the laboratory. As illustrated in Figure 4, this fault further shows how diffused, plastic movements are concentrated into one, more elastic displacement, doubtless with great increase in velocity, until it attains an observed speed of 1-1/2 inches per year. Farther north and deeper, where the movement is divided among perhaps 10,000 surfaces on each of which the velocity need not exceed 1/10,000 of that just mentioned, even the tectonic force may not be elastically applied, for it seems possible that an elastic strain in the rock may set too fast to let it cause such slow movement. Regardless of the value of the preceding argument, which has no quantitative basis, the fine subdivision of the gliding along the northern or deeper part of the shear-zone proves that toward its source the shearing is increasingly plastic, which indicates that the transmission of the force itself is plastic.

These ideas may bear also on major features of Earth-deformation. The high confining

pressure of great depths probably causes very fine spacing of glide-planes, that is, high plasticity. The gliding would enter the upper crust at its weakest place and most effectively from the side of a geosyncline where the less plastic initiation of the gently rising flow had created the upwarp that delivered most of the sediment to the corresponding downwarp (geosyncline). On that side the force of the flow would be greatest, causing the most deformation in the strata, and in crossing the geosyncline the plastically transmitted force would decline until deformation became negligible. At first, elastic effects would intervene only where there was sufficient concentration and acceleration of the gliding and only in the last stages would elasticity rule the deformation.

The transmission of tectonic force by a plastic stream is undirectional along the line of flow. The expression "pressure from the southeast," long condemned by linguistic purists, may now acquire better standing, for, in its clumsy way, it tries to express the upstream direction in the current of plastodynamic force. External constraints may deflect the stream and retard parts of it, so causing sinuosity in a folded range. The sharp loops in the Alpine system could not have resulted from a push by elastically acting, or relatively strong, rock; indeed, the massifs that are regarded as autochthonous parts of the sub-Alpine basement are highly schistose, having shared in the flow instead of acting like the rigid jaws of a vice. In places, the otherwise softly behaving nappes, buried their heads under the south sides of massifs, as though the latter had been the weaker, instead of the stronger. There every formation flowed and the amount of differential flow or internal gliding increased downward toward each sole and an unknown distance down into the far-from-rigid basement. The main directions of flow are those of primary transmission of plastodynamic force and of its secondary, diverted branch-streams. A survey of alpha-lineation and of orthogonal joints, dikes, and veins should reveal these directions more accurately than any map of the undoubtedly rotated axes of folds.

Main conclusions

The plastic element is thought to have been underestimated in previous treatments of rock-deformation, including faults, on many of which the writer believes that displacement was "fed" by diffused plastic gliding and, in some cases, was dissipated plastically from the faults. Small, sympathetic brancnes of a tear-fault that are placed so as to be able to "feed" strike-slip to the main fault diverge from the latter toward the direction of major pressure. The invisible sub-branches of these must trend still closer to that direction, and those of the diagonal tear-faults of the Jura Mountains and the diagonal faults in the experimental folding of soft clay by Cloos must nearly or quite coincide with that direction. Indeed, the Cloos experiments reveal orthogonal joints along the "direction of major pressure" that run into the diagonal faults.

Analysis of alpha-lineation in rock, in air (clouds), and in water indicate that in all three states of matter it represents the same phenomenon, namely, gliding along steep planes that cut the low-lying glide-sheets along the line of flow (alpha). In rock these appear to be orthogonal planes, normal to the original position of the axes of ordinary types of folding or of other beta-lineation, a position of gliding that is impossible under the dynamics of solids. In other words, the initial phenomenon in rock seems to be fully hydrodynamic but, since it grades into a later, less liquid action, it will be called "plastodynamic."

"Ebb-and-flow" shearing designates a type of shear-folding that is due to reversal in the sense of shearing along alternating, subequally spaced glide-planes, or groups of glide-planes, which follow a younger cleavage that crosses an older one at high angle. The dynamics of solids does not allow shearing to have opposite sense on alternating, parallel planes. In a solid, there is no direction of major stress that could produce "ebb-and-flow" structure, which, however, could arise from liquid flow along the younger cleavage. Here, again, the phenomena seem essentially hydrodynamic but, since they occur in rock, they will be called "plastodynamic."

Although there is some trace of an early, more elastic part of a few cycles of deformation, the part most generally detected is one of decreasing plasticity of deformation. Various cases may be explained by cooling, by a lessening of the pressure normal to glide-planes, and by other causes that promote the slipping of wider groups of shear-sheets, or by other types of concentration of gliding upon fewer surfaces, such as the "feeding" of displacement to the latter.

Orthogonal joints are thought to originate along a selected few of many invisible, orthogonal planes of very small, plastic gliding that accommodates the lateral inequality in the forward advance within glide-sheets that may have any inclination to force. The closely spaced orthogonal glide-planes are thought to facilitate the primary flow along the direction of transmission of plastodynamic force. A relatively small number of them may be rendered visible as joints, where there was

greater shearing along them, or where there was tension across them in a later, more elastic phase of deformation. They are favored loci of dikes and veins. The surfaces of orthogonal joints, though generally not striated, are as smooth as any shear-joints, except where they lie along well-developed alpha-lineation, where they are rougher, yet never as rough as typical tension-joints, such as those of a basaltic column. Orthogonal joints are the only ones that commonly occur in positions that are suitable for the "feeding" of displacement to tear-faults.

These and other inferences expressed in the paper are but tentative and are subject to great change, for it is only a preliminary attempt to outline a few aspects of "plastodynamics."

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AMERICAN GEOPHYSICAL UNION

TWENTY-FIRST ANNUAL MEETING

April 24-27, 1940

MINUTES GENERAL ASSEMBLY AND SECTIONS

Washington, D.C.

April 26, 1940

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Minutes, General Assembly and Sections, Twenty-First Annual Meeting (1940)

BUSINESS SESSION

The Business Session of the General Assembly of the American Geophysical Union was held Friday, April 26, 1940, in the Library of the National Academy - Research Council Building, Washington, D. C. The Session was called to order at 12:00 noon by the President, R. M. Field, there being 40 members present [see Appendix A].

The minutes of the twentieth annual meeting on April 28, 1939, were approved as published in the Transactions of 1939.

The General Secretary's report for the year [see Appendix B], presented in abstract, was accepted and ordered printed in full in the Transactions of 1940.

The President reported informally, voicing the accomplishments of the Union during the past year and the Union's appreciation of the work done by the General Secretary and by the former Chairman of the Organizing Committee for the Seventh Triennial Assembly of the International Union of Geodesy and Geophysics.

Reports of standing committees

Chairman L. H. Adams of the Committee on Meetings stated that the sections of the Union have been increased from seven to eight with the formation of the new Section of Tectonophysics, which had an unusually large attendance and much interesting discussion. He also remarked that there appears to be in all of the sections of the Union an ever-increasing interest and enthusiasm. On the social and semi-scientific side, the smoker held April 25 was attended by 130 persons.

Chairman J. A. Fleming of the Editorial and Publication Committee reported that the Transactions of 1939 were prepared and distributed with the exception of copies for some geophysicists abroad which could not be forwarded because of the war conditions, that the Bibliography of Hydrology for the United States for the year 1938 was published last year and preparations are under way for planographing the Bibliography for 1939, and that manuscripts are in hand for the Stanford meeting of the Section of Hydrology which will form Part I of the Transactions of 1940.

Reports of special committees

In the absence of Chairman Maurice Ewing of the Special Committee on Geophysical and Geological Study of Oceanic Basins, Dr. Hess made an informal report; the report was ordered printed in the Transactions [see Appendix C].

The report [see Appendix D], presented in abstract, of Chairman W. T. Thom, Jr., for the Special Committee on Geophysical and Geological Study of Continents was accepted and ordered printed in full in the Transactions.

The report of Chairman H. T. Stetson for the Special Committee on Cosmic Terrestrial Relationships was presented in abstract and was accepted and ordered printed in full in the Transactions [see Appendix E].

Chairman H. E. McComb of the Special Committee on Time-Signal Service presented the following report:

"The excellent schedule of radio time-signals originating at the United States Naval Observatory and broadcast by several Naval radio stations has been continued throughout the year. The 113-kilocycle signal, broadcast hourly, has proved to be of special value at fixed stations equipped with special equipment for recording these signals automatically. The high-frequency signals, especially those at 9425 and 9090 kilocycles, are excellent for use in the field as well as at fixed stations, since elaborate equipment is not necessary for their reception.

"It has recently come to the attention of the Committee that it would be desirable to have more signals from the Naval station at Balboa, Canal Zone, in order to provide somewhat better service for field-parties and fixed stations in Central and South America."

At the suggestion of Mr. McComb, a motion was carried to have him prepare a resolution thanking the Naval Observatory and other cooperating organizations for their help in furthering the work of the Committee.

Chairman William Bowie of the Special Planning and Project Committee presented a report, which was ordered printed in the Transactions [see Appendix F].

Chairman W. T. Thom, Jr., of the Special Exhibits Committee made the following report:

"The Special Exhibits Committee, in its original capacity as a sub-unit of the Organizing Committee for the Seventh General Assembly of the International Union of Geodesy and Geophysics, prepared approximately 50 special exhibits [for description and price-list, see Appendix G] which were illustrative of the kinds of geophysical-geological study being fostered by Special Committees of the American Geophysical Union.

"During the sessions of the Seventh Assembly, and subsequent thereto, it became evident that much, if not all, of the original costs of preparation of the special exhibits could be recovered through the sale of copies of these several 'Special-exhibit' maps and diagrams, and hence the Special Exhibits Committee [Maurice Ewing, W. T. Thom, Jr. (Chairman), and G. P. Woollard] was continued by the Executive Committee of the Union to arrange for and to handle the distribution of these materials. More than three hundred copies of special exhibits have been sold, and an appreciable part of their total cost has been recovered by the Union. Now that it should soon be possible to construct other special exhibits which will be of both general use and interest, it is hoped that it will be possible to recapture the whole of the outlays which have been made in connection with preparation of the special exhibits."

Chairman J. B. Macelwane of the Special Committee on Repository for Fundamental Geophysical Data reported as follows:

"The report will be very brief. For the benefit of those who are not familiar with the history of the Committee we should state that the project came originally from Sherwin F. Kelly to our Special Planning and Project Committee and through it to the Executive Committee of the Union. The Executive Committee approved the project and appointed this Committee to study the means of executing it. The Committee met in New York City and again in Washington, and discussed the project from every angle. As the Committee sees it, the project resolves itself into three parts. The first is educational, that is, to bring the country to a realization of the valuable character of the geophysical records that have been gathered at such great cost by commercial agencies. The second is to enlist the interest of responsible executives who possess these records to a point where they would be willing and anxious to preserve them for science of the future in a repository. The third is the creation of such a repository itself, or of a system of repositories. Certainly, that triple objective cannot be treated by parts. The three will have to be taken into account more or less simultaneously. It seemed to the majority of those present at the Washington meeting that if there is any existing national agency in the country which is fitted to sponsor such a project--not at present within the province of any of the governmental departments--it is our National Research Council. It also seems to the Committee that the entire project is one which would be eminently worthy of the attention and consideration of that Council."

Chairman L. P. Disney submitted a written report for the Special Committee for Cooperation with International Commission for Study of Tidal Waves [see Appendix H].

Chairman W. C. Lowdermilk of the Special Finance Committee presented a report [see Appendix I]. Upon the President's suggestion, the Committee's recommendations were referred to the Executive Committee of the Union for further discussion and action.

Resolutions

The Committee on Resolutions [J. P. Marble (Chairman), Harry Hess, and O. W. Torreson] then submitted through Chairman Marble the following six resolutions, each of which was adopted upon motion:

(1) RESOLUTION ON REPOSITORIES FOR GEOPHYSICAL RECORDS (submitted by Special Committee on Repository for Fundamental Geophysical Data)

WHEREAS, There exists in the files of commercial companies a vast body of data which has been collected by geophysical exploration at enormous expense, and

WHEREAS, A considerable portion of this information is now no longer of commercial value and is therefore in danger of destruction, and

WHEREAS, This would constitute an irreparable loss to science, as many have pointed out, therefore be it

RESOLVED, That the American Geophysical Union and the Committee on Geophysics of the National Research Council express their whole-hearted approval of the efforts that have so far

been made to preserve these records and in particular of repositories for geophysical records such as that created at Saint Louis University.

(2) RESOLUTION ON COMPILATION AND INVESTIGATION OF SOUNDING DATA (submitted by Special Committee on Geophysical and Geological Study of Oceanic Basins)

WHEREAS, The number of soundings obtained by the United States Navy has increased a hundredfold since sonic sounding has taken the place of wire-sounding in the deep sea, and

WHEREAS, These soundings are now being plotted on master charts as a result of a project of the Works Progress Administration, and

WHEREAS, The information to be obtained from these soundings is of great value to science, especially if compiled and studied by a scientist familiar with topographic forms and contouring, therefore be it

RESOLVED, That the American Geophysical Union and the Committee on Geophysics of the National Research Council express their whole-hearted approval of any effort to obtain support for a project to make it possible for a scientist to assist in a compilation and investigation of sounding data at the Hydrographic Office of the United States Navy.

(3) RESOLUTION ON SEISMOGRAPHIC STATIONS IN THE NORTH ATLANTIC (submitted by Section of Seismology)

WHEREAS, Due to conditions abroad, seismographic stations in the North Atlantic may be forced to suspend operation, and

WHEREAS, These stations are of the utmost importance for the location of epicenters and for the study of the crustal structure of the Atlantic Basin, therefore be it

RESOLVED, That the American Geophysical Union and the Committee on Geophysics of the National Research Council recommend to the Department of Commerce, in whose province seismological research in the United States comes, that it make every reasonable effort to assure continued operation of these stations.

(4) RESOLUTION ON SEAWARD EXTENSION OF SUBMARINE VALLEYS (submitted by Special Committee on Geophysical and Geological Study of Oceanic Basins)

WHEREAS, Accurate bathymetric charts of the continental shelf and slope to a depth of approximately 1,000 fathoms are now available as a result of the work of the United States Coast and Geodetic Survey, and these charts show submarine valleys of much interest to science, and

WHEREAS, Further information concerning the seaward extension of these valleys out on to the ocean-floor proper would be of much value to science, therefore be it

RESOLVED, That the American Geophysical Union and the Committee on Geophysics of the National Research Council place themselves on record as heartily in favor of obtaining such soundings as would be necessary to investigate the seaward extension of one or more of the submarine valleys, and be it further

RESOLVED, That governmental agencies capable of carrying out such an investigation be encouraged to do so.

(5) RESOLUTION ON ANALYSIS AND PUBLICATION OF DATA ON RAINFALL AND RUNOFF (submitted by Section of Hydrology)

WHEREAS, The American Geophysical Union recognizes the deficiency of factual information essential for an intelligent and economic solution of practical hydrologic problems, and

WHEREAS, Many basic data having a direct bearing upon the solution of such problems are now in existence, and

WHEREAS, The National Resources Planning Board has pointed out in its message to the President dated March 2, 1940, major deficiencies in present research, and

WHEREAS, The analysis of such data is essential for judging and directing needed future research, therefore be it

RESOLVED, That the American Geophysical Union and the Committee on Geophysics of the National Research Council recommend that the full influence of such bodies as the National Research Council be used to stimulate the analysis of the accumulated data on rainfall and associated runoff together with the publication of such data and their analysis.

(6) RESOLUTION ON UNITED STATES NAVAL OBSERVATORY TIME-SIGNALS (submitted by Special Committee on Time-Signal Service)

WHEREAS, The continuation of the excellent schedule of precise time-signals originating at the United States Naval Observatory and broadcast by the Navy Department from its various radio stations is of the utmost importance in many special as well as routine geophysical operations in the field and at fixed observatories, therefore be it

RESOLVED, That the American Geophysical Union and the Committee on Geophysics of the National Research Council express to the Navy Department their full appreciation for the continued maintenance of this highly useful time-service, and be it further

RESOLVED, That a copy of this resolution be sent to the Secretary of the Navy.

Elections

The Committee on Nominations [L. H. Adams (Chairman), C. L. Garner, and W. T. Thom, Jr.] nominated J. A. Fleming for reelection as General Secretary of the Union for the three-year period ending June 30, 1943. There were no other nominations from the floor and J. A. Fleming was unanimously reelected.

The sections reported the election of the following officers: Section of Geodesy--W. D. Sutcliffe, Secretary, for three years from July 1, 1940; Section of Volcanology--Earl Ingerson, Secretary, to fill unexpired term of James Gilluly through June 30, 1941; newly formed Section of Tectonophysics--L. H. Adams, President, R. A. Daly, Vice-President, and David T. Griggs, Secretary, all for period through June 30, 1943.

The meeting adjourned at 1:06 p.m.

SCIENTIFIC SESSION

The scientific session, beginning at 2:33 p.m. with 115 members and guests present [see Appendix A], was devoted to a symposium on tectonophysics of the crust as printed in these Transactions.

Just preceding the presentation of papers, the second award of the Bowie Medal of the American Geophysical Union honoring unselfish cooperation in geophysical research was made to Arthur L. Day. T. Wayland Vaughan read the citation of Dr. Day as follows:

"Mr. President: The Committee on the William Bowie Medal of the American Geophysical Union presents to you as the duly nominated and selected recipient of the William Bowie Medal, Arthur Louis Day. Dr. Day's activities may be briefly outlined as follows:

"Between 1900 and 1904 Dr. Day studied experimentally at the United States Geological Survey the equilibrium in the plagioclase feldspars at high temperatures, and these researches were followed in 1904 by the initiation of an endeavor to extend high-temperature thermometry above 1150° C.

"In December 1905 the Carnegie Institution of Washington appropriated funds for the erection of a Geophysical Laboratory, the activities of which were placed under the direction of Dr. Day. The results of the Geophysical Laboratory cannot be summarized on this occasion--their scope can only be mentioned. They have included gas-thermometry to 1550° C with extrapolations to the melting point of platinum, the equilibrium-studies of the melting relationship of many systems of rock-forming oxides, the elastic properties of solids (including the determination of the compressibility of typical rocks and the calculation of the speed of earthquake waves in such material), the study of volcanoes and hot springs, and radioactivity.

"Besides his personal researches and his direction of the operations of the Geophysical Laboratory, Dr. Day has been instrumental in helping to enlist the assistance of the United States Navy in making submarine surveys by acoustic methods off the coast of California in 1923, and in placing at the disposal of Professor F. A. Vening Meinesz a submarine for gravity-surveys in the Caribbean region in 1928.

"In addition to the accomplishments outlined, Dr. Day served as Chairman of the Advisory Committee on Seismology of the Carnegie Institution of Washington from 1921 to 1936. It would take too much time to review the accomplishments of this Committee. Only its purpose will be stated: 'To establish, with the highest precision attainable, the present position of all useful surface landmarks, both above and beneath the sea; to measure the aggregate displacements of the past on active faults; to discriminate strained portions of the Earth's crust from unstrained and to seek out the forces which operate to produce strains; to discover the composition, the physical structure, the geologic age, the density, and the elastic properties of the rocks which compose this composite crust, and in particular the zones of structural weakness in it; to develop instruments competent to analyze and measure elastic tremors, differences in pressure, and density; and to study any other factors which may affect the stability of the structure under observation. In this manner it is hoped to attain to a competent knowledge of the character, the proximate causes, and trend of development (in both time and space) of the Earth-movements of the region selected for the initial studies (California).'

"Dr. Day is eminent for his own personal researches, for his leadership in the establishment of the foremost research laboratory in any country for the investigation of numerous geophysical and geochemical problems, and for his part in promoting cooperative effort in several different fields of geophysical research. We honor ourselves in honoring Dr. Day."

President Field then presented the Medal and Dr. Day replied as follows:

"Mr. President, Dr. Vaughan, and friends: Since I was not provided in advance with a copy of the details which you have just heard, I am not equipped with a proper antidote. I suspect, however, in view of the program that is before us this afternoon, that brevity is a major consideration.

"There are really two features of this award which should receive some emphasis. One is the fact that I have had associated with me about 40 men of abundant research experience without whose cooperation these achievements which have been read to you would not have been possible. This award of the William Bowie Medal is, therefore, in recognition, as I take it, of a long series of cooperative efforts extending over about 35 years, to enter and effectively develop a particular field of geophysical research, namely, the study of the relationships of the components of the Earth's crust and of the forces acting upon them during the formation processes. This has been the major task of the Geophysical Laboratory to which, as I like to interpret it, this award is primarily directed.

"As a matter of record the American Geophysical Union is younger than the Geophysical Laboratory. I cherish the fact that the American Geophysical Union was started, so far as its active early work was concerned, in this city. I grew up with it. The value placed on any man's activity by his immediate associates is real and is not greatly colored by sentiment. The fact that many of you, perhaps most of you, have grown up with me in Washington and that we have worked together on these problems of geophysics for so long, makes me particularly appreciative that this award should have come in just this way and from this American Geophysical Union. I thank you."

The Committee on Meetings [L. H. Adams (Chairman), C. F. Brooks, D. Griggs, J. P. Marble, and H. T. Stetson] was commended for the excellent program developed which resulted in the great success of the twenty-first annual meeting of the Union as evidenced by the papers published in this present volume of Transactions.

The meeting adjourned at 5:32 p.m.

The minutes of the meetings of the Sections of the American Geophysical Union, April 24-27, 1940, are given in attached Appendix J.

(Signed) Jno. A. Fleming, General Secretary,
American Geophysical Union

APPENDIX A--RECORD OF 551 MEMBERS AND GUESTS WHO REGISTERED ATTENDANCE AT GENERAL ASSEMBLY OF THE UNION AND AT SESSIONS OF ITS SECTIONS, TWENTY-FIRST ANNUAL MEETING, APRIL 24-27, 1940

(Total number in attendance was considerably in excess of those registered.)

(1 = Business session of General Assembly; 2 = Scientific session of General Assembly; a = Geodesy; b = Seismology; c = Meteorology; d = Terrestrial Magnetism and Electricity; e = Oceanography; f = Volcanology; g = Hydrology; and h = Tectonophysics.)

Abernethy, W. E. (d)
Adams, Leason B. (a)
Adams, L. H. (1,2,f,h)
Adkins, John N. (2,h)
Aldredge, R. C. (c)
Allen, Alice S. (f)
Anderson, B. J. (e)
Anderson, C. N. (a)
Arctowski, Henryk (2,c,g)
Ash, A. D. (g)
Ashburn, E. V. (c)
Averitt, Paul (e,f)
Avers, H. G. (e)
Axelrod, Joe (f)
Bailey, R. K. (f)
Baker, A. A. (2,a)
Balsam, Ella (d,f)
Bancroft, Dennison (2,h)
Barksdale, Henry C. (1,g)
Bartels, J. (2,d)
Beij, K. H. (1,g)
Benfield, A. E. (2,e)
Bennett, R. R. (g)
Bernard, M. (g)
Bestul, S. M. (a)
Birch, F. (2)
Bittinger, Charles (b)
Blair, Wm. R. (c)
Blaisdell, F. W. (g)
Blake, Archie (2,b,h)
Blumenstock, D. (c,g)
Blythe, R. H., Jr. (g)
Boardman, Leona (f)
Bodle, R. R. (2,b,h)
Bogart, D. B. (g)
Boland, Wm. A. (c)
Bomquend, E. H. (g)
Bond, J. A. (e)
Borden, F. S. (a,b,e)
Boucher, Roland J. (c)
Bowen, N. L. (2,f,h)
Bowie, W. (1,2)
Boyer, M. C. (g)
Bradford, Gershom (e)
Bradley, W. H. (2,a,e,g,h)
Brady, James M. (c)
Bramlette, M. N. (2,e,f)
Brancato, G. N. (c)
Brands, M. D. (g)
Brannock, W. W. (g)
Brashears, M. L., Jr. (g)
Bray, J. T. (g)
Bristor, C. (c)
Brooks, C. F. (c,g)

Brotzman, L. E. (c)
Brown, Alice L. (b,c)
Brown, C. B. (g)
Bryan, G. S. (e)
Bryson, R. P. (2)
Bucher, Walter H. (2,h)
Buell, C. E. (c)
Burbank, W. S. (2,f)
Burchard, Ernest F. (b)
Burlew, John S. (f)
Burnett, E. L. (g)
Burrill, Meredith F. (c)
Byers, Alan C. (2,b,d,g,h)
Cady, R. C. (g)
Calcano, Miguel (a)
Callaghan, E. (2,f)
Callaway, E. B. (e)
Campbell, F. B. (g)
Cannon, Ralph S. (2,f)
Capello, J. J. (1,2,b,d,e)
Carson, Ernest (c)
Cederstrom, D. J. (g)
Chauny, P. de (c)
Chauny, Mme. P. de (c)
Cheesman, W. L. (c)
Clark, C. O. (g)
Clemence, G. M. (a)
Clifford, Charles J. (a)
Cloos, Ernst (h)
Clough, H. W. (c)
Coats, Robert (f)
Cochran, A. L. (g)
Colbert, L. O. (a,b,e)
Cole, J. S. (g)
Cole, L. A. (e,g)
Colin, Charles H. (c)
Collins, E. B. (e)
Connaughton, M. P. (g)
Cortright, H. M. (g)
Crawford, Gerald P. (c)
Croft, A. R. (g)
Crowl, G. H. (2,f,g)
Culbert, G. A. (c)
Culley, F. L. (a,h)
Cullings, E. S. (g)
Dalrymple, T. (g)
Davenport, R. W. (1,g)
Davis, F. H. (g)
Davis, W. E. (2,g)
Day, Arthur L. (2)
Delaney, John P. (b,h)
Demorest, Max (2,a,e,h)
Demorest, Rebecca H. (2,a,h)
Dennison, I. A. (g)
Denson, N. M. (2,f)
Devereaux, W. C. (c)
Diebold, C. H. (g)
Dinger, C. C. (c)
Disney, L. P. (e)
Dobson, G. C. (g)
Dorsey, H. G. (e)
Dove, W. N. (d,h)
Draper, Glen H. (a)
Drawbaugh, W. B. (c)
Duerksen, J. A. (2,a,e)
Du Pré, M. B. (g)
Duvall, Wilbur I. (h)
Eaton, H. N. (g)
Edmonston, H. R. (e)
Einstein, H. A. (g)
Eisenlohr, Wm. S., Jr. (1,g)
Eldridge, F. R. (d)
Emmons, G. (c)
Fahey, Jos. J. (f)
Farnham, F. C. (1,2,a,d,g,h)
Ferguson, G. E. (g)
Ferguson, H. E. (2)
Ferris, J. G. (g)
Fiedler, A. G. (g)
Field, R. M. (1,2,a,b,d,e,h)
Fine, H. J. (g)
Fishel, V. C. (2,g)
Fisher, Lawrence C. (c)
Fleischer, Michael (2,f)
Fleming, Jno. A. (1,2)
Fogel, E. H. (d)
Forbush, S. E. (2,d)
Foster, M. D. (g)
Foster, W. R. (2,b,f,g)
Frank, B. (g)
Fraser, Donald M. (f)
Frazier, A. H. (g)
Fritz, S. (c)
Garner, C. L. (1,2,a,d,e)
Garstka, W. N. (g)
Gasque, J. O. (b)
George, J. J. (c)
Geyer, J. C. (g)
Geyer, R. A. (a,d,f,h)
Gilbert, C. G. (c)
Gish, O. H. (1,2,f,g)
Glass, Jewell J. (2,f,h)
Glymph, L. M., Jr. (g)
Goddard, E. N. (2,f)
Gold, H. K. (g)
Goldman, Marcus I. (2,f,h)
Goodridge, R. S. (1,2,g)
Goranson, Roy W. (2,f,h)
Grant, J. A. (g)
Graves, G. Van A. (c,e)
Greenfield, M. A. (d)
Greening, G. K. (c)
Greig, J. W. (2,f,h)
Griggs, David (2,f,h)
Griggs, Robert F. (f,h)
Grover, N. C. (1,g)
Grunwell, G. B. (a)
Gunn, Ross (d)
Gurnee, M. S. (g)
Guthe, Otto E. (c,g)
Hafstad, K. C. (c)
Haight, F. J. (g)
Haines, W. C. (c)
Hand, I. F. (c)
Hansen, P. T. (a)
Harkness, F. B. (g)
Harper, F. H. (c,g)
Harradon, H. D. (1,2,c,d)
Harrold, J. C. (g)
Harrold, L. L. (g)
Hartley, Henry (e)
Hathaway, G. A. (g)
Haurwitz, B. (2,c)
Haynes, B. C. (c)
Heck, N. H. (1,2,b,d,e,h)
Heckler, W. L. (g)
Hellweg, J. F. (a)
Hemple, H. W. (a,e)
Hendricks, T. A. (2,a,d,f)
Hendrix, W. C. (2,d,e)
Hermansen, E. (g)
Hern, J. D. (g)
Herndon, J. M. (g)
Hersey, J. B. (2,e,h)
Hertzler, R. A. (g)
Hess, H. H. (1,2,b,e,f,h)
Holtan, H. N. (g)
Holzman, B. (c,g)
Hood, F. C. (g)
Horn, Egmont (f,h)
Horner, W. W. (g)
Horton, J. (g)
Horton, R. E. (g)
Howard, C. S. (g)
Howard, G. W. (g)
Howe, H. H. (d)
Hoyt, W. G. (g)
Hubbert, M. K. (2,a,h)
Huff, T. F. (d)
Hulburt, E. O. (d,e)
Humphreys, W. J. (c)
Hunt, C. B. (2,f)
Hunter, H. C. (c)
Hurd, Willis E. (f)
Hurwitz, L. (d)
Ingerson, Earl (1,2,b,f,h)
Insley, Herbert (f)
Iselin, C. O'D. (e)
Jacob, C. E. (2,a,g,h)
Jakl, V. E. (c)
Jarvis, C. S. (g)
Johnson, E. A. (d)
Johnson, J. W. (g)
Johnson, M. E. (g)
Johnston, H. F. (2,d)
Jones, A. B. (g)
Jones, B. E. (g)
Jones, Edwin H. (c)
Jones, Mark W. (d)
Jones, P. R. (c)
Jordon (b)
Joyce, J. W. (2,d,e)
Judson, Lewis V. (a)
Kalbfleisch, A. C. (a)
Kaufman, H. P. (e)
Kazmann, R. G. (g)
Keith, Arthur (1,2,e,h)
Kelly, Grace W. (1,2,d)
Kenworthy, P. W. (c,g)
Keppel, David (f)
Kesler, Thos. L. (f)
Keulegan, G. H. (g)
Kiehl, H. R. (d,f)
Kincer, J. B. (c)
Kinnear, E. R. (g)
Kirby, S. S. (d)
Kirpich, Z. P. (g)
Klaer, F. H., Jr. (g)

Knopf, Adolph (2,f,h)
Knopf, Eleanora B. (2,f,h)
Korff, S. A. (d)
Koschmann, A. H. (2,f)
Kracek, F. C. (f)
Krampe, C. M. (d)
Krimgold, D. B. (g)
Kuehn, H. E. (2)
Ladd, Harry S. (f)
Lamar, W. L. (g)
Lambert, W. D. (1,a,h)
Lammers, Edw. C. H. (d,f,h)
Lance, T. D. (2,f)
Landsberg, H. (1,2,b,c,h)
Lane, A. C. (2,d,f)
Lang, W. B. (a,g,h)
Langbein, W. B. (g)
Larrabee, J. H. (e)
Ledig, Paul G. (2,d,f)
Lee, F. W. (d)
Leggette, R. M. (g)
Le Lacheur, E. A. (e)
Lennahan, C. M. (c)
Lewis, Isabel M. (d)
Li, Changhai (a,d,e)
Lichtblau, Stephen (c)
Liferock, M. (a)
Light, P. (g)
Little, D. M. (c).
Lloyd, L. (g)
Lohman, K. E. (2,f,h)
Longwell, C. R. (a,h)
Loughlin, G. F. (f)
Love, S. K. (g)
Lovering, T. S. (2,f)
Lowdermilk, W. C. (1,2,c,d,g,h)
Lowry, H. W. (g)
Ludy, A. K. (1,2,b,d)
Lynch, William A. (1,b)
Lyons, W. S. (a)
Lyons, R. R. (e)
MacCarthy, G. R. (a,d,f)
Macelwane, J. B. (1,2,b,f,h)
Macurdy, Lloyd (a)
Mansfield, G. R. (b,f,h)
Marble, A. H. (h)
Marble, J. P. (1,2,b,d,e,f,h)
Markowitz, Wm. (a)
Marmer, H. A. (e)
Marshall, E. D. (g)
Martin, L. (g,h)
Mask, W. S. (g)
Mason, M. A. (g)
Mason, W. D. (g)
Mathews, O. R. (g)
Matthes, F. E. (1,g)
Mattice, W. A. (g)
Mauchly, J. W. (c,d)
Mavis, F. T. (g)
Mayhew, H. B. (e)
McCall, A. G. (g)
McComb, H. E. (1,b)
McCombs, Chas. (a)
McDonough, S. J. (d,h)
McGee, Bernard C. (b)
McGuinness, C. S. (2)
McNeal, Don (c)
McNiff, William T. (1,b)
McNish, A. G. (2,a,d,h)
Mears, I. T. (c)
Medina, Guillermo (e)
Meinzer, O. E. (g,h)
Merewether, A. F. (c)
Merriam, C. F. (g)
Merritt, George E. (b)
Metcalfe, E. O. (e)
Meyer, R. C. (d)
Mikesell, Alfred H. (a)
Miller, M. (d)
Milton, Charles (f)
Minogue, J. A. (c)
Mitchell, G. S. (g)
Mitchell, George (c)
Mitchell, Hugh C. (a)
Molen, J. P. (c)
Montgomery, R. B. (e)
Moore, A. Lee (a)
Moorman, L. S. (c)
Morey, G. W. (f)
Morgan, H. A. (a)
Munns, E. N. (g)
Muntz, C. L. (g)
Murray, Harold W. (e)
Murto, H. C. (g)
Musgrave, G. W. (g)
Muskat, M. (2,a)
Myers, Arthur J. (c)
Myers, Earl C. (1,g)
Nadai, A. (h)
Naramore, W. W. (d)
Neiburger, Morris (c)
Nelson, J. H. (b)
Nelson, Wilbur A. (h)
Nemenyi, P. (g)
Nettleton, L. L. (2,a,h)
Neumann, Frank (2,b)
Newlin, Delmas B. (a)
Nichols, L. L. (e)
Nichols, R. L. (f)
Noble, W. M. (g)
Nolan, T. B. (2,h)
Norris, C. (a)
Oak, W. W. (c)
Obert, Leonard (h)
Odell, H. H. (g)
O'Keefe, D. M. (c)
Olmstead, L. B. (g)
Osborn, E. T. (2)
Osborn, E. F. (f)
Ould, R. S. (d)
Overitt, Paul (2)
Owen, J. C. (g)
Page, B. L. (a)
Page, L. F. (c)
Park, Charles F., Jr. (2,f,h)
Parkhurst, D. L. (e)
Parkin, Ernest J. (a)
Patterson, G. W. (g)
Pawling, Jesse (a,c)
Peoples, J. A., Jr. (2,a,b)
Peoples, Joe Webb (f)
Peterson, B. J. (g)
Petritic, G. J. (g)
Pierce, W. G. (2)
Pietsch, W. R. (g)
Prince, A. T. (2,b,f)
Prince, C. T. (g)
Prior, C. H. (g)
Rahmlow, H. W. (c)
Randall, Dwight L. (c)
Rappleye, Howard S. (a)
Reading, O. S. (a,e)
Reed, T. R. (c)
Reeves, M.D. (g)
Reichelderfer, F. W. (c)
Reid, Harry Fielding (2,b,h)
Reynolds, Walter F. (a)
Rice, Donald A. (a)
Rich, John L. (1,2)
Riesbol, H. S. (g)
Riggs, R. J. (2,a,d,h)
Risher, C. L. (c,g)
Ritchie, Don C. (a)
Roberts, K. L. (g)
Roberts, Ralph J. (f)
Roes, J. S. (d,f)
Roger, C. L. (2)
Roman, Irwin (2,a,b,d,f)
Rooney, W. J. (b,c,d,e)
Root, E. (d)
Root, R. E. (c)
Rosenman, M. (a)
Rosenthal, J. R. (c)
Ross, Clarence S. (f)
Rossby, C. G. (c)
Rubey, W. W. (2,d,e,h)
Rynearson, G. A. (f)
Sallsman, C. J. (c)
Sampson, Edward (2)
Samuels, L. M. (e)
Samuels, L. T. (c)
Saville, T. (g)
Schairer, J. F. (2,f)
Schaller, W. T. (f)
Schlossman, Louis (d)
Schworm, S. S. (c)
Scofield, C. S. (g)
Scott, W. E. (2,d,e)
Seaton, S. L. (d,e)
Seiwell, H. R. (2,e)
Shofnos, William (e)
Shands, A. L. (c)
Shanklin, G. R. (g)
Sharpe, C. F. S. (g)
Shelton, John (h)
Sherman, K. L. (2,c,d,h)
Sherman, L. K. (g)
Short, M. N. (2)
Showalter, A. K. (c)
Shropshire, R. F. (e)
Sik, A. E. (c)
Sims, I. H. (g)
Skeels, D. C. (2,a)
Small, James B. (a)
Smith, Ed. H. (e,g)
Smith, Paul A. (e)
Smith, Kenneth E. (c)
Smith, Newbern (d)

Smith, R. W. (g)
Smith, W. E. (g)
Smith, Ward (2,f)
Snyder, F. F. (g)
Sohon, F. W. (2,b)
Sollenberger, Paul (a)
Solot, S. B. (c)
Soroka, M. Q. (g)
Spencer, A. C. (b,h)
Spicer, H. C. (2,a)
Spilhaus, A. F. (c)
Stadnichenko, Taisia M. (h)
Staponick, Edward F. (c)
Starr, W. K. (g)
Stearn, J. L. (a)
Stechschulte, V. C. (1,2,b,d,f,h)
Steenland, N. C. (b,d,f,h)
Steiner, W. F. (d,e)
Stephens, G. T. (c)
Stephenson, E. B. (e)
Stephenson, H. K. (h)
Stetson, H. T. (1,2,a,c,d,e,h)
Stevens, L. A. (c)
Stevens, R. E. (f)
Stewart, Ralph (f)
Stirni, A. R. (a)
Stokes, W. L. (2,b)
Stone, R. C. (c,g)
Stose, Anna J. (f)
Stose, Geo. W. (f)
Stow, M. H. (a,f,h)
Straub, L. G. (g)
Stringfield, V. T. (g)
Sutcliffe, W. D. (a,h)
Swainson, O. W. (b,d,e)
Swartz, J. H. (d,f)
Swenson, B. (g)
Swick, C. H. (1,a,d,e,h)
Tatge, Eleanor (f)
Taylor, George F. (c)
Tepper, Morris (a)
Thayer, T. P. (f)
Thom, H. C. S. (g)
Thom, W. T., Jr. (1,2,b,h)
Thomas, H. A. (g)
Thompson, D. G. (g)
Thompson, H. J. (c)
Thornthwaite, C. W. (c,g)
Tibbott, E. W. (a)
Torreson, O. W. (1,2,d)
Trask, P. D. (2,a,e,g)
Tunell, G. (f)
Turnbull, J. (g)
Turner, L. M. (g)
Underwood, P. H. (1,2,a,d,e,h)
Unger, E. E. (c)
Urry, W. D. (2)
Vacquier, V. (1,2,a,b,d,h)
Van Orstrand, C. E. (2)
Vaughan, T. Wayland (1,2,e)
Vederman, Joseph (c)
Vernon, G. R. (e)
Vestine, E. H. (b,d)
Vhay, J. S. (2,b,f)
Vroman, G. M. (g)
Waanenen, A. O. (g)
Wait, G. R. (d,h)
Wallis, W. F. (d)
Warren, H. A. (g)
Warren, W. C. (f)
Washburne, Mrs. Chester W. (h)
Watt, W. G. (e)
Watts, C. B. (a)
Wayland, Russell G. (f)
Weber, J. L. (g)
Weggel, H. A. (g)
Wells, F. G. (f)
Wells, R. C. (f)
Wenzel, L. K. (g)
Wexler, H. (c)
Whitcroft, Thos. H. (e)
Whitten, C. A. (a,e)
Wilgus, A. S. (e)
Willett, H. C. (c)
Williams, Earl L. (a)
Williams, G. R. (g)
Williams, Howel (f)
Williamson, R. O. (a)
Willis, J. E. (a)
Wilm, H. G. (g)
Wilson, James T. (2,h)
Wilson, R. M. (1,a)
Wilson, W. T. (g)
Woodworth, R. W. (a)
Wolfe, A. Y. (c)
Woodring, W. P. (2)
Wright, Fred E. (2,a,b,h)
Wulf, Oliver R. (2,c,d)
Young, V. D. (g)
Zimmerman, J. S. (g)
Zuckerman, Irving (d)

APPENDIX B--REPORT OF THE GENERAL SECRETARY OF THE AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-FIRST ANNUAL MEETING, APRIL 26, 1940

The minutes of the twentieth annual meeting held April 28, 1939, were printed in the Transactions of 1939 (Part III, pp. 454-481) and were distributed to all members of the Union, to authors of papers presented at the meeting, and to officers of the International Union of Geodesy and Geophysics. No suggestions for changes or corrections have been received.

Three members of the Union have died since the last annual meeting: L. T. Jessup, affiliated with the Section of Hydrology; A. E. Kennelly, June 18, 1939, affiliated with the Section of Terrestrial Magnetism and Electricity; D. C. Barton, July 22, 1939, affiliated with the sections of Geodesy, Seismology, and Terrestrial Magnetism and Electricity.

The total membership of the Union April 26, 1940, is 1,264--a net gain of 140 during the past year. A new address-list of members of the Union will be issued soon based on information received from a circular letter sent to all members on January 25, 1940.

The Executive Committee held two meetings since the last report (December 21, 1939, and April 9, 1940). Copies of the minutes of these meetings were distributed to members of the Executive Committee and to officers of the sections.

The necessary arrangements were made for the twenty-first annual meetings of the Union and of its sections in Washington April 24 to 27, 1940, the program for the scientific sessions including some 124 papers and progress-reports.

After some preliminary editing by the secretaries of sections and by the chairmen and Dr. J. E. Church for the regional meetings, the General Secretary edited and prepared for publication in the Transactions of 1939 (four parts totaling 741 pages) the 114 papers and reports presented during the twentieth annual meeting at Washington and 39 papers and reports with discussions presented during the meetings of the Section of Hydrology and of the Western Interstate

Snow-Survey Conference at Los Angeles and Spokane. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, and contributions of money and of services from the Carnegie Institution of Washington, from the University of Nevada, from members of the Union, and especially from hydrologists--both members and non-members. Over 1,800 bound copies of these Transactions have been distributed to members of the Union, to authors of papers presented, to foreign geophysicists including members and non-members of national committees for geodesy and geophysics, to institutions and scientific societies, to review periodicals, to persons on the regular mailing-list of the National Research Council, and by sale.

A regional meeting for the South Pacific Area of the Section of Hydrology and of the Western Interstate Snow-Survey Conference was held at Stanford University, California, January 12 and 13, 1940, under the chairmanship of F. J. Veihmeyer of the South Pacific Area. Arrangements have also been made for a regional meeting of the North Pacific Area and the North Continental Divide Area of the Section of Hydrology jointly with the Western Interstate Snow-Survey Conference and in conjunction with the meetings of the American Association for the Advancement of Science at Seattle, Washington, June 20 to 23, 1940, with J. C. Stevens as Chairman of the Committee on Arrangements. A regional meeting of the Section of Hydrology is also planned for Pennsylvania State College, State College, Pennsylvania, June 30 to July 3, 1941.

The Bibliography of Hydrology, United States of America, for the Year 1938 (72 pages) was prepared in an edition of 1,200 from manuscript prepared by the Secretary of the Section of Hydrology. The required number of copies was forwarded to the Secretary of the International Association of Scientific Hydrology. The Section of Hydrology has appointed Miss Mary O. Soroka as Chairman of a Committee on Bibliography, and she is proceeding with the preparation of the manuscript for the Bibliography for 1939 to be published as in preceding years.

The publication of the Richmond symposium of December 1938 on "The importance of geophysics to the study of continental borders" has now been arranged by the Permanent Secretary of the American Association for the Advancement of Science. Advice has been received that the manuscripts of the symposia on "Application of mathematics and Earth's physics" and "Hydrologic problems in the Ohio and Michigan basins," held jointly with the American Association for the Advancement of Science at the Columbus meeting in December 1939, are being assembled. In case the manuscripts are submitted for publication, the Executive Committee of the Union has given authority to include them with the Transactions of 1940.

The National Research Council has included in its estimates for the fiscal year ending June 30, 1941, a grant of $400 to the Union. After consulting with the General Secretary's office, a budget totaling $8,300 has been submitted by the Budget Committee of the Union for expenses of publication and maintenance during that fiscal year. The estimated income includes: (1) Balance in bank, July 1, 1940, $1,400; (2) income from 1940 dues, $3,600; (3) grant from National Research Council, $400; (4) sales of Transactions, reprints, and special-exhibit maps, $2,900.

An Auditing Committee examined the accounts of the Union as of date December 31, 1939, and reported the receipts and disbursements exactly as stated in the General Secretary's report of that date.

As in the past, the Union cooperated with the Division of Physical Sciences of the National Research Council in the preparation of special bulletins on geophysical methods, instruments, results, etc. Since the last meeting, Volume VII entitled "Internal constitution of the Earth" edited by B. Gutenberg and Volume VIII entitled "Terrestrial magnetism and electricity" eidted by J. A. Fleming in the series "Physics of the Earth" of the National Research Council have been printed. Progress has been made on the preparation of the special volume on hydrology in this series.

The mail ballot resulting from the circular letter of January 25, 1940, sent to all members of the Union on the formation of a Section of Tectonophysics and on necessary amendments to the Statutes and By-Laws, indicated an overwhelming majority in favor of the new Section and the necessary amendments, and favorable action in this connection was accordingly taken by the Executive Committee. Already over 300 members have expressed their desire to be affiliated with the new Section of Tectonophysics, which is to promote and encourage research of fundamental importance to our knowledge of earth structure not covered in any one of the other sections of the Union.

The following Special Committees have been appointed since the twentieth annual meeting:

On Award of Bowie Medal--T. Wayland Vaughan (Chairman), William Bowie, H. N. Eaton, J. W. Greig, J. W. Joyce, F. Neumann, and F. W. Reichelderfer; Finance Committee--W. C. Lowdermilk (Chairman), L. H. Adams, R. M. Field, J. A. Fleming, and C. O. Iselin.

A considerable number of black and white copies of the special-exhibit maps prepared by the Union for the Washington Assembly of the International Union of Geodesy and Geophysics last September have been sold as a result of circularizing interested persons and organizations by the Special Exhibits Committee. The list of special exhibits includes a total of 50 maps.

St. Louis University has been designated as a central repository for fundamental geophysical data which may be released by petroleum companies and exploration organizations.

The Special Committee on Geophysical and Geological Study of Oceanic Basins reports good progress despite European conditions which have interfered greatly with work at sea. A second seismic component has been installed at Bermuda. Cooperative work has been done with the Woods Hole Oceanographic Institution in the Gulf Stream. During the past year over $10,000 has been contributed for the work of this Committee by the American Philosophical Society, the National Geographic Society, and the American Geographical Society. Gravity-measurements in the Caribbean are being planned, largely through the generous loan of gravity-apparatus by the Humble Oil and Refining Company.

The commissioning of the non-magnetic ship Research was interfered with by the war, but late advices from the Hydrographer of the British Admiralty indicate that she is quite safe and that there is still a small amount of work to be done before she is ready to take up research work on the high seas.

The Union was represented by several delegates at the Sixth Pacific Science Congress held during July 24 to August 12, 1939, at Berkeley and Stanford University. These included B. Gutenberg, P. Byerly, H. U. Sverdrup, T. G. Thompson, and E. H. Vestine.

Upon the cordial invitation of the Honorable Secretary of State Cordell Hull to participate in the Eighth American Scientific Congress to be held in Washington May 10 to 18, 1940, the following members of the Union were designated as its official delegates: L. H. Adams, L. V. Berkner, William Bowie, G. S. Bryan, L. O. Colbert, R. M. Field, J. A. Fleming, N. C. Grover, N. H. Heck, E. O. Hulburt, C. O. Iselin, W. C. Lowdermilk, J. B. Macelwane, C. H. Swick, W. T. Thom, Jr., and E. G. Zies. Several members of the Union have been called upon to present papers bearing on special geophysical subjects.

The Seventh General Assembly of the International Union of Geodesy and Geophysics was held at Washington, September 4 to 15, 1939. Thanks to the whole-hearted cooperation of the members of all the committees on arrangements under the enthusiastic and generous leadership of N. H. Heck, Chairman of the American Organizing Committee, adequate preparations had been made for the reception and entertainment of some 800 delegates and guests. The actual attendance of delegates and guests was 719, while the total number of delegates who had been appointed and guests who had promised to attend was 947. There were 120 delegates from abroad, while 126 could not attend because of the war which had broken out just before the Assembly convened, some of whom were already in America but had to be called back before the beginning of the Assembly. The total number of delegates and guests from the United States who had indicated their intention to attend was 701, but the actual attendance was only 599 largely because of the fact that an incorrect notice appeared in the press to the effect that the Assembly would be postponed, and the time was then too short to correct it. The number of countries represented by delegates and guests including the United States was 38. In addition to those from European countries, were fortunate in having representation from six governments of the Western Hemisphere besides the United States.

The exclusion of administrative matters and discussion of matters pertaining to statutes and finances left greater opportunity for the presentation and discussion of scientific papers and reports. The topics discussed at the Assembly ranged from the small-scale local changes in geophysical conditions caused by mineral deposits and the water-regimen of a typical alpine glacier watershed to the world-wide seismic vibrations initiated by the big earthquakes and the large-scale oceanic currents. More than other branches of science, geophysical research depends on international collaboration. A unique example of this was evidenced in the recent solar outbursts during the last days of March which caused auroral and geomagnetic disturbance affecting communication by radio and cable all over the Earth without regard to political frontiers. The idea of international collaboration dominated the proceedings and appeared so obvious to all that it was hardly mentioned. The fact that under great political stress no discord marred the harmony of the meetings must be regarded as a success well earned by the presidents and officers of the

International Union and of its Associations and by the leaders of the American Geophysical Union who, as congenial hosts, rose to the occasion in providing perfect facilities and an immemorable atmosphere of good-will and cooperation.

Despite the unfortunate circumstances of the European war, it was the general consensus of opinion that the Seventh General Assembly will be numbered among the most successful and profitable which the Union has held. This was made possible largely through the generosity in the provision of funds for the necessary expenses by the Carnegie Corporation of New York, Geological Society of America, and National Research Council, as well as equal contributions from members and friends of the American Geophysical Union, all resulting through the efforts of the Finance Committee under the effective chairmanship of R. M. Field.

Thus far, some 3,500 requests have been received for copies of the Transactions of the Washington Assembly of the International Union and of its seven Associations for distribution in the United States.

A check has been received from the Treasurer of the United States for $3,920.40 covering the dues of the United States as an adhering member of the International Union of Geodesy and Geophysics for the calendar year 1939. This money is to be deposited in the special account of the International Union at the Riggs National Bank after appropriate authorization is received from the Executive Committee of the International Union.

Dark clouds are now hovering over many countries of the world, but these cannot be everlasting. The Union may rejoice in its part to advance the scientific and economic aspects of geophysical research and the coordination of international and national activities through its sections and its special committees.

(Signed) Jno. A. Fleming, General Secretary
American Geophysical Union

APPENDIX C--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEANIC BASINS

Maurice Ewing, Chairman

F. Birch	E. A. Eckhardt	P. MacClintock	F. M. Soule
J. Boyd	J. A. Fleming	A. G. McNish	H. C. Stetson
W. H. Bradley	B. Gutenberg	W. A. Nelson	H. U. Sverdrup
G. S. Bryan	N. H. Heck	C. S. Piggot	C. H. Swick
W. H. Bucher	H. H. Hess	L. A. Richards	W. T. Thom, Jr.
L. O. Colbert	C. O. Iselin	W. W. Rubey	T. G. Thompson
E. G. Conklin	H. Landsberg	F. P. Shepard	P. Weaver
R. E. Dickenson	L. R. Leahy	P. A. Smith	F. E. Wright

The Committee has discussed with officials of the Navy Department the bearing of the present international situation upon scientific investigations which are carried out at sea. As a result of these discussions it is in a position to give advice on this question to members of the Union or other scientists who contemplate work at sea.

Special investigations of the Committee have been continued with particular emphasis on improved methods for the measurement of gravity at sea, for seismic measurements on the ocean-floor, and for photography on the ocean-bottom.

Lehigh University,
Bethlehem, Pennsylvania

APPENDIX D--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

W. T. Thom, Jr., Chairman

L. H. Adams	A. L. Day	M. K. Hubbert	G. R. Mansfield
A. C. Bevan	E. DeGolyer	J. W. Joyce	O. E. Meinzer
N. L. Bowen	M. Ewing	S. F. Kelly	E. L. Perry
W. Bowie	J. A. Fleming	E. S. Larsen	L. B. Slichter
O. C. Branner	S. E. Forbush	F. W. Lee	O. W. Torreson
A. F. Buddington	C. L. Garner	C. R. Longwell	H. R. Wanless
P. Byerly	J. Gilluly	T. S. Lovering	B. B. Weatherby
R. T. Chamberlin	O. H. Gish	J. B. Macelwane	Howell Williams
E. Cloos	D. T. Griggs	H. E. McComb	G. P. Woollard
R. A. Daly	B. Gutenberg	A. G. McNish	

During the year ended April 1940, the chief functions of this Committee have continued to be cooperative and catalytic participation in the advance of geophysical-geological research pertaining to continental areas and borders.

A dinner-meeting, held jointly with the Special Committees on Oceanic Basis and on Cosmic Terrestrial Relationships at the time of the 1939 annual meeting of the Union, led subsequently to the appointment of a subcommittee to consider what formal actions were needed to advance the vital field of tectonophysics. After careful deliberation, this subcommittee [L. H. Adams, A. F. Buddington, J. Gilluly, D. T. Griggs (Chairman), and M. K. Hubbert] reported as follows:

"Recent developments in theoretical study, experimental investigation, and geophysical field-observations promise to have so many important applications to fundamental Earth science that, in the opinion of the subcommittee, progress of the science of geophysics would be materially advanced if there were to be formed within the American Geophysical Union a new section, the purpose of which would be to promote and encourage projects of fundamental importance to our knowledge of Earth structure, and specifically to bring together for report and discussion at the meetings of the Union those experts whose work would make important contributions to the subject of tectonophysics. The subcommittee therefore proposes the constitution of a 'Section of Tectonophysics' of the American Geophysical Union.

"It is to be clearly understood that such a new section would in no wise infringe upon the activities of the existing sections, but it is believed would stimulate parallel development in those sections whose methods and observations are contributory to the solution of problems in tectonophysics.

"Tectonophysics (the term coined by Dr. N. L. Bowen) is the physics of elastic deformation, flow, and rupture of the constituent materials of the Earth. Some of the specific lines of endeavor which come under this heading are the following:

"(1) Physical theory of flow and rupture with applications to geological problems

"(2) Mechanism of deformation of rocks and minerals--(a) Evidence from experiments; (b) deductions from field and petrofabric analysis

"(3) Experimental and deductive studies of the stress-fields in the Earth's crust--(a) Model experimentation on problems of structure; (b) field-measurements of earth-movements and rock-creep; (c) geophysical analysis and interpretation of geologic structures

"(4) Forces available for deformation and fracture in the Earth

"(5) Thermal phenomena of importance in the development of Earth structures

"Geophysical measurements in the last ten years have supplied new information of the utmost value in interpreting Earth structures. The need for coordination of physical and geological efforts has been recognized by the International Union of Geodesy and Geophysics in constituting the International Commission on Continental and Oceanic Structure, and by the American Geophysical Union in establishing its Special Committees on Geophysical and Geological Study of Continents and of Oceanic Basins. The growing need for physical and geological cooperation on studies of the 'Mechanics of deformable bodies' with applications to Earth problems has been stated in the report of the National Research Council Interdivisional Committee on Borderland Fields between Geology, Physics, and Chemistry, under the chairmanship of Dr. T. S. Lovering [1937].

"Because of this increasing demand for cooperation on problems of Earth structure; because of the increasing number of men contributing to solutions of these problems; and because the American Geophysical Union is the only organization in which physicist, geophysicist, and geologist may meet to discuss these problems; the subcommittee recommends to the Executive Committee of the American Geophysical Union that a new section of the Union be formed, to be called the 'Section of Tectonophysics', with the express purpose of providing a formal channel for discussion of these results which find no outlet in the present program of the Union."

This report and proposal were considered and approved by the Committee as a whole, and were

transmitted to the Executive Committee of the Union with a favorable recommendation. Subsequently, after careful consideration of the matter, both by the Executive Committee and by the membership of the Union as a whole, the proposal was formally approved and adopted, and the new Section of Tectonophysics was accordingly created.

In collaboration with sub-units of the Organizing Committee for the Seventh General Assembly of the International Union of Geodesy and Geophysics, this Committee also revised and expanded its contour-map showing the configuration of the surface of the basement-complex beneath the eastern and central parts of the United States. This map, and a relief-model constructed therefrom, became, respectively, numbers 1 and 50 among the collection of the American Geophysical Union's Special Exhibits displayed during the Seventh General Assembly.

Members of this Committee also collaborated with the Organizing Committee for the Seventh General Assembly by assisting in a field-demonstration (for foreign members of the Assembly) of the geological problems of the Appalachian Geosyncline, and of the geophysical-geological approaches thereto, as deducible during a field-excursion from the St. Lawrence lowland and Adirondack uplift southwestward to Elmira, New York, and State College, Pennsylvania, and thence southeastward to Harrisburg and Washington.

Members of the Special Committee have also cooperated during the year with the Geophysical Section of the American Institute of Mining and Metallurgical Engineers in its survey of the status and needs of North American geophysical education.

This Committee also has cooperated with Professor C. R. Longwell, Chairman of the Division of Geology and Geography of the National Research Council, in working out plans whereby the Huesteca Petroleum Company and the Humble Oil and Refining Company are each placing a gravity-meter on continuing loan with the American Geophysical Union--for use on geophysical-geological research projects recommended by this Committee and approved by the Union. As an initial experiment in the use of the Humble's meter for general continental study, Dr. G. P. Woollard, National Research Council Fellow in Geophysics at Lehigh University, has just been voted a project grant of $3,000 from the Penrose Fund of the Geological Society of America wherewith to undertake a detailed gravity-meter traverse, which will probably begin on the California Coast west of Bakersfield and extend thence eastward and northeastward across the San Joaquin Valley, the Sierra Nevada, Death Valley, the Great Basin region, the Colorado Rockies, and the Interior Lowland--this traverse to be ultimately continued to Pittsburgh (if and when possible) to make a tie there with the Gulf Research and Development Company's existing gravity-meter profile from Pittsburgh to Washington to Baltimore. The above-mentioned project is under the authority of the Geological Society of America. This Committee, as agent of the American Geophysical Union, has merely served in an advisory capacity with reference to the plans being laid, and as an active agent in the securing and reloaning of the Boucher x-type gravity-meter, which the Humble Company has loaned to the Union.

Upon completion of the transcontinental gravity-traverse project just mentioned, both meters will be available either for research use by the Union's Special Committees on Geophysical and Geological Study of Continents and of Oceanic Basins, or for loan to Government agencies having special responsibilities for gravitational research.

In concluding, this Committee wishes to express its appreciation to the Humble and Huasteca companies for their generous assistance in lending the two gravity-meters, and also wishes to record its belief that the researches which will thus be made possible will have great ultimate significance to Earth science--in both its "applied" and "not-yet-applied" phases.

Princeton University,
Princeton, New Jersey

APPENDIX E--REPORT OF SPECIAL COMMITTEE ON COSMIC TERRESTRIAL RELATIONSHIPS

Harlan True Stetson, Chairman

W. Bowie	J. A. Fleming	J. Kaplan	H. R. Morgan
C. F. Brooks	N. H. Heck	G. W. Kenrick	F. R. Moulton
H. H. Clayton	J. F. Hellweg	W. D. Lambert	P. Sollenberger
A. E. Douglass	E. A. Hodgson	H. Landsberg	J. Q. Stewart
M. Ewing	E. O. Hulburt	A. C. Lane	W. T. Thom, Jr.

In the first report of this Committee at the annual meeting of the Union, 1939, emphasis was placed upon certain fundamental geophysical problems necessitating scientific cooperation in such widely diversified fields as astronomy, geology, meteorology, and engineering.

The questions raised in our first report concerning variations in geographic coordinates in their relationship to structural geology has continued to receive the attention of members of the Committee together with certain fundamental problems of the atmosphere where extra-terrestrial factors are involved.

Variation in latitude--The important position which the United States Naval Observatory holds in fundamental positional astronomy means much to the work of this Special Committee through the cooperation of its representatives--Captain J. F. Hellweg, Dr. H. R. Morgan, Mr. Paul Sollenberger, and their coworkers. The continued operation of the photographic zenith-tube provides fundamental data for investigation of variations in geographic coordinates at Washington. During the past year extensive study of the dependence of latitude-variation upon the position of the Moon has been undertaken by Messrs. Markowitz and Bestul at the Naval Observatory, utilizing a method of analysis similar to that used by Sollenberger and Clemence in studying the variation in longitude reported last year. Detailed results are being presented to the Section of Geodesy of the Union. The examination of data extending from November, 1915, to January, 1940, indicates tidal effects observed at Washington, in accordance with usual gravitational theory. This is somewhat at variance with the results which have been obtained from correlations of latitude-variations with lunar hour-angles and lunar altitudes for observations covering intervals of time of more than three years. The fact that the coefficients obtained from an harmonic analysis on the assumption of a sinusoidal distribution of residuals does not disclose the amplitudes exhibited when sine-functions are not assumed, suggests the need of further investigation. It seems possible that significant irregular variations may be lost when an harmonic analysis is applied on the assumption of a sine-curve variation with fixed period.

It is to be regretted that no other photographic zenith-tube is in operation elsewhere. It is possible that records obtained with similar instruments in locations of fundamentally different geologic structure than that of Washington might yield results bearing upon questions of structural geology. One cannot overlook important contributions made by the latitude-station at Gaithersburg in cooperation with the International Latitude-Service, but the need for long continuous observations of latitude at other points selected from geological considerations is still to be emphasized. Aside from the motion of the Earth's pole of rotation, it seems to be only a question of time when astronomical observations will be able to detect horizontal displacements of a secular nature, particularly in localities where diastrophism is likely to be most active. The interdependence of star-positions upon geographic coordinates places our Naval Observatory in a strategic position for contributions in this field.

Variation in longitude--The question of variation in longitude is fundamentally in the same category with that of the variation in latitude. It has perhaps more often been segregated for consideration by special investigators and commissions because of the somewhat different technique involved. Whereas in latitude-variation star-positions and micrometric measurements at the meridian-passage of stars are the fundamental factors, the variation of longitude involves in addition the mechanism of the exact time-determination of star-transits and the reliability of timekeeping devices for measuring the interval between transits. Here also we are distinctly dependent upon international cooperation.

The reestablishment of the 17-kilocycle time-signal between Great Britain and the United States reported last year has not as yet resulted in a sufficiently long series of data to justify intensive study. Communication difficulties have so far entailed considerable loss in the number of exchanges of time-signals possible. For several months GBR did not broadcast on the 17-kilocycle frequency due possibly to war considerations. The Committee is happy to report, however, that the British long-wave signal has again been reestablished. Captain Hellweg and Mr.

Sollenberger of the Naval Observatory have reported interference in receiving the British signal on account of an harmonic of the crystal-clock synchronizing at the same frequency as the British signal. It has been thought that a new receiver, placed at a more remote region in the Observatory, may improve the situation locally. Ionospheric disturbances, such as have occasionally happened during the year, have probably in part accounted for interrupted reception. Such difficulties beyond the observer's control will probably occur less frequently as solar activity subsides.

Project for the timing of radio wave-velocities--The project planned two years ago for timing the transmission of radio time-signals from east to west, as compared with west to east, by transporting a crystal-chronometer aboard a plane has been delayed partly through the absence of Dr. Ewing on account of other important geophysical work and also on account of the difficulties of securing adequate flight-facilities. Attempt is being made to contact certain airlines with the hope that a plane may be loaned for the purpose without expense to the Committee. Dr. Ewing has suggested certain modifications of the experiment as was originally proposed that will make possible a preliminary result without the extended flight originally projected. In the modified form of the experiment, two crystal-chronometers would be needed and the Committee hopes that the chronometer formerly in the custody of the Union and subsequently loaned for work abroad may again be available for this purpose, since the European situation shows little likelihood of making possible the work for which the chronometer was originally loaned.

Solar-terrestrial effects--The dependence of time-signal propagation upon ionospheric conditions has previously been emphasized and furnishes one of several important reasons for the investigations of electromagnetic phenomena of the upper air as influenced by extra-terrestrial factors.

Several members of the Committee have undertaken during the year investigations of relationships between solar, atmospheric, and geomagnetic phenomena. In this connection much important work has been done by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. This has been excellently summarized in the annual report of the Director, Dr. Fleming, a member of our Committee. The important question of the general magnetic field of the Sun has been raised through the existence of diurnal variation in cosmic rays. Results from various investigators are still somewhat indefinite as indicating the importance of the supposed magnetic field of the Sun in producing diurnal variation. As has been pointed out, a reinvestigation of the Sun's general magnetic field would be helpful because of its important bearing on many geomagnetic problems. Dr. Fleming reports that a high correlation between the activity of electric currents in the Earth and solar activity as measured by sunspot-numbers has been more completely verified and that this correlation has been shown to hold even for month-to-month variations.

The Committee takes this occasion to emphasize the invaluable contributions of the Department of Terrestrial Magnetism with its branch stations not only in providing irreplaceable data but in the painstaking analysis of observations intimately associated with problems of cosmic terrestrial relationships and hopes that observations of terrestrial electricity and geomagnetism shall not only be continued but extended in this field of geophysics open for exploration.

Dr. Brooks, Director of the Blue Hill Meteorological Observatory and member of our Committee, has placed at our disposal the long and valuable records of auroras as reported at Blue Hill. Investigation of the relationships between solar activity, the occurrences of auroras, and resultant disturbances in field-strengths in the broadcast band, together with transmission-conditions on short-wave reception, and the general magnetic character of the day has been published by the Chairman in the current number of Terrestrial Magnetism and Atmospheric Electricity.

From a study of the same list of auroras Mr. Clayton has made a study of the frequency of auroras at Blue Hill and the numbers and distributions of sunspots during the last 55 years. Both of these investigations show the tendency for the maximum auroral displays to occur one or two years after the year of maximum solar activity. Mr. Clayton also concludes from his investigation that both size and latitudes are important factors in the effect of sunspots on resulting auroras and shows that statistically larger areas are necessary in high-latitude spots to produce terrestrial effects noted from less disturbed areas at lower solar latitudes. Mr. Clayton has also been investigating the distribution of atmospheric high- and low-pressure areas in the Northern Hemisphere for any possible correlation with solar radiation and activity. He finds some evidence for tracing the 27-day rotation-period of the Sun in certain atmospheric oscillations during the years 1936 and 1937.

It is anticipated that the valuable list of auroral observations at Blue Hill will be published in the near future and thereby become generally available.

Dr. C. W. Gartlein of Cornell University, in addition to photographic and spectroscopic studies of auroras, has made an interesting study of auroras visible at Ithaca during the last two years. His studies have shown a tendency for recurrence at 27-day intervals and afford a valuable contribution to this field.

Cosmic-research laboratory--A new laboratory for cosmic-terrestrial research in connection with the Massachusetts Institute of Technology has been inaugurated in the suburbs of Boston. After considerable study as to possible locations a site was selected in the rural districts of Needham reasonably free from electric and magnetic interference. The situation, ten miles southwest of Boston, remote from any manufacturing center, provides conditions reasonably free from atmospheric pollution from the metropolitan area since the prevalent winds are westerly and southwesterly. At this station quantitative measurements of field-strengths of WBBM, Chicago, have been continued. The accumulation of these field-measurement data grows in importance with the years as affording material for many geophysical investigations. There has also been designed and set up at the laboratory a pliotron ion-counter for the study of variations in small ions of the atmosphere and provision has been made for continuously recording earth-to-sky and sky-to-earth electrical discharges through the installation of a point-discharge recorder. It is hoped shortly to install suitable facilities for continuously recording the potential-gradient of the atmosphere and for recording geomagnetic variations.

Through the active cooperation of Dr. Landsberg and the courtesy of the Bausch and Lomb Optical Company, the laboratory has been supplied with special glass rods for measuring the ultra-violet in sunshine. The degree of discoloration of this special glass is a measurement of the integrated ultra-violet received during each day's exposure and should form a valuable supplement to other methods for measuring variations in ultra-violet at the Earth's surface.

Dr. Kenrick has continued his ionospheric investigations at Puerto Rico. Early results have already emphasized the high critical frequencies for San Juan which were predicted several years ago. Critical frequencies observed at this station appear higher than those observed either at Washington or Peru. The effect appears to persist during 24 hours. Such results indicate the desirability of ionospheric measurements near the magnetic equator to supplement those made at greater latitudes. Dr. Kenrick emphasizes the need for funds for continuing his observational program. The value of such results obviously lies in the length of the series of measurements which can be made.

The unusual magnetic storms of Easter week with the accompanying auroral displays arousing wide interest in cosmic-terrestrial phenomena served to emphasize the need of continuing atmospheric-electric and geomagnetic observations in all parts of the world. In spite of the disturbed situation in Europe, the Committee on Cosmic Terrestrial Relationships of the American Geophysical Union has kept in close touch with the Commission for the Study of Solar and Terrestrial Relationships of the International Scientific Radio Union, and hopes that the work of the American Committee may be of special help to this Commission during these times when the work in other countries is unavoidably interrupted. The importance of close cooperation among workers in allied fields cannot be over-emphasized.

Massachusetts Institute of Technology,
Cambridge, Massachusetts

APPENDIX F--REPORT OF SPECIAL PLANNING AND PROJECT COMMITTEE

William Bowie, Chairman
A. G. McNish, Secretary

L. H. Adams	R. M. Field	S. F. Kelly	J. B. Macelwane
C. F. Brooks	J. A. Fleming	C. O. Iselin	L. K. Sherman

The Committee considered a number of projects during the past year which have been submitted to it at previous times. A resolution has been drawn up by the Committee and submitted to the Executive Committee of the Union urging continuation and extension of regular observations supplying reliable data on the variability of solar radiation in pursuance of a project submitted to the Committee by C. G. Abbot.

The Committee has also been active in furthering a recommendation of the Special Committee on Geophysical and Geological Study of Continents for the establishment of a repository for geophysical data. It will be of interest to the Union to know that a Special Committee has been appointed by the Union to take up this important work.

Although there are still a few projects upon which no definite action has been taken, the Committee urges members of the Union to submit any suggestions for furtherance of activities in geophysics. The Committee's original appeal to members of the Union for such suggestions met with a very favorable response [see Trans. Amer. Geophys. Union, 19th annual meeting, 1938, pp. 575-577]; it is hoped that members will continue to avail themselves of the services of this Committee in promoting projects of either a general or specific nature.

For some years the Union has been giving its attention and support to national mapping. Although the Committee has taken no formal action on this project, it is interesting to know that greater activity in this field will be realized during the coming fiscal year. The appropriation to the United States Coast and Geodetic Survey is $450,000 for field-work as compared with only $80,000 last year. For topographic mapping it is likely that $2,000,000 will be available, partly as a direct appropriation to the United States Geological Survey and partly as an appropriation to the civil activities of the War Department. The United States Geological Survey is receiving $725,000 for the present year as its regular appropriation for topographic mapping. In addition, the Survey will receive $252,000 from States that are engaged in cooperative topographic surveying which will be available presumably during the next fiscal year. The amounts of money to be appropriated for geodetic surveys and topographic mapping are about half that recommended in a report to the Senate by the Secretaries of Commerce, War, and Interior [Senate Document No. 54, present session]. In that report appropriations of $5,000,000 were recommended for the first year, $6,000,000 for the second year, and $7,000,000 for the third year, and thereafter at least $7,000,000 per annum until the map-needs of the people of this country had been taken care of. It seems probable that these appropriations for geodetic surveys and topographic mapping represent the inauguration of a plan of national mapping with its great attendant value to many branches of geophysical investigations.

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

APPENDIX G--AMERICAN GEOPHYSICAL UNION SPECIAL EXHIBIT (NO. 1), RECONNAISSANCE-MAP SHOWING APPROXIMATE CONFIGURATION OF SURFACE OF BASEMENT-COMPLEX

Statement as to purpose and manner of preparation

Following the establishment of the American Geophysical Union's Special Committee on Geophysical and Geological Study of Oceanic Basins in 1932 a companion Special Committee on Geophysical and Geological Study of Continents was organized in 1935--its two chief purposes being to make "a cooperative and simultaneous application of geophysics and geology in an attack upon the major problems of Earth composition and evolution" and to develop (known) "calibration"-areas whence geophysical traverses could advantageously be extended into and across sub-oceanic regions. Since the seismic (refraction) method and other geophysical exploratory techniques may yield results which relate particularly to the configuration and structure of the surface of the basement-complex, and since a three-dimensional model is much more easily readable than a structure contour-map, one of the first endeavors of the Special Committee on Continents was to assemble a reconnaissance contour-map--for the area between the Rocky Mountain front and the Atlantic Coast--in order that a "basement-surface" relief-model of this region could be constructed. This map and model were exhibited at the American Geophysical Union's annual meetings in April 1936 and at the Sixth General Assembly of the International Union of Geodesy and Geophysics held in Edinburgh during the summer of 1936. Subsequently this basement-map was revised and was extended westward to the edge of the Great Basin to include the geosynclinal structural zone extending northward across western Wyoming, eastern Idaho, and western Montana, and a new relief-model was made--the map and model constituting, respectively, Special Exhibits 1 and 50 prepared by the American Geophysical Union for display at the Seventh General Assembly of the International Union held in Washington in September 1939.

The methods used by the Committee in preparing Special Exhibit 1 (and its preliminary version) are ones familiar to those engaged in exploration for oil. In essence they consisted (1) of plotting the locations and elevations of "basement (that is, pre-Cambrian) rock" outcrops, (2) of plotting the locations of deep wells (drilled for oil or water) which have reached the basement, with indication of the sea-level elevation of the basement at such points, and (3) of using these surface and subsurface control-points (plus such geophysical evidence as was non-confidentially available) in contouring the basement-surface by extrapolation from the United States Geological Survey geologic map of the United States, and from the many regional subsurface contour-maps and cross-sections which have been published by various State geological

surveys, by the American Association of Petroleum Geologists, by the Kansas Geological Society, and by the other regional geological societies which have been active in collaborative studies of subsurface conditions over the greater part of the United States.

At the present time one cannot even guess the depth to the basement-surface in the deeper structural troughs (such as that of the Appalachians), but it may prove possible to determine these depths hereafter by geophysical means. As exploration progresses, and as the results of past explorations cease to have competitive value, it will undoubtedly be possible to expand, revise, and correct the contouring now shown on parts of Special Exhibit 1, and the pattern of known or inferrable basement-faults will undoubtedly need revision and amplification. It is almost certain, however, that the changes which will be needed will be of relatively local character, and that they will not greatly modify the total picture--which provides a reference-frame that will undoubtedly be particularly helpful in the interpretation of exploratory results hereafter to be obtained in the basins of the western Atlantic and of the Gulf of Mexico.

Table 1 lists the maps so far prepared by the Committee.

Table 1--List of American Geophysical Union special exhibits
(Assembled for Seventh General Assembly, International Union of Geodesy and Geophysics, 1939)

No.	Description	Number of sheets	Size of whole map (no margins) N-S inch	Size of whole map (no margins) E-W inch	Price postpaid
1	Reconnaissance structure-contour map of surface of basement-complex in U.S.	4	45 1/4	72 1/2	$4.00
2	Iso-anomaly map of U.S., 60-km depth of compensation (1936)	2	48	75 3/4	4.00
3	Iso-anomaly map of eastern U.S., 113.7-km depth of compensation (1938)	1	47	35 1/2	2.00
4	Normal warp iso-anomaly map of U.S. (1937)	1	46	40	2.00
5	Gravitational and structural trends in eastern U.S.	1	40	27 1/2	2.00
6	Gravity-profiles across eastern U.S. (1938)	1	16	16 3/4	0.25
7	Geologic map of the U.S. (U.S. G.S. Pub.)	4	50	75	....[a]
8	United States seismic-epicenter map	1	42	78 1/2	3.00
9	"Geothermal-gradient" map of the U.S.	4	45	72 3/4	3.50
10	Map showing variation of carbon-ratios of Cretaceous and Tertiary coals in U.S.	1	29 1/4	37 1/4	1.00
11	Map showing variation of carbon-ratios of Carboniferous coals in the U.S.	1	24 1/2	34	1.00
12	Geologic map of Beartooth-Bighorn-Black Hills Region	1	28 1/2	69 1/2	3.00
13	Iso-anomaly map of Beartooth-Bighorn Region	1	38 1/4	43 1/2	2.00
14	Normal warp iso-anomaly of Beartooth-Bighorn-Black Hills Region	1	28	52	1.25
15	Geologic and gravitational profiles across Beartooth-Bighorn-Black Hills Region	1	16 3/4	41 1/2	0.75
16	Geologic map of New Jersey (N.J. State G.S. Pub.)	1	46 1/2	25	....[b]
17	Seismic and geologic cross-section for Barnegat Bay traverse, New Jersey	1	26	48 1/2	1.25
18	Cape May, New Jersey, seismic and geologic profiles	1	32	70	4.00
19	New Jersey velocity-gravity sections on Cape May and Barnegat Bay profiles	1	40 1/2	36 3/4	2.00
20	Structural analysis of geologic-seismic data for the Plainsboro area, New Jersey	1	22 1/2	41 3/4	1.00
21	Map showing extension of the Palisades Diabase (N.J.) based on magnetic and geologic data	1	18 1/4	40 3/4	0.75
22	Key map showing location of geophysical sections across Atlantic Coastal Plain	1	27 1/4	19 1/4	0.75
23	Geologic map of Virginia Region	1	19 1/2	24 1/4	0.50
24	Basement-surface contour-map, Virginia	1	18 1/4	25 1/4	0.50
25	Gravity iso-anomaly map of Virginia Region	1	18 3/4	25	0.50
26	Seismic, gravitational, and geologic profiles for Cape Henry, Virginia, and Barnegat Bay, N.J., sections	1	18	19 1/2	0.50
27	Geologic, gravitational, and "computed-density" sections across Virginia Region	1	16 3/4	23 3/4	0.50
28	Bathymetric map of Bermuda area	1	17	19 1/2	0.50

Table 1--Concluded

No.	Description	Number of sheets	Size of whole map (no margins) N-S	Size of whole map (no margins) E-W	Price post-paid
			inch	inch	
29	Bathymetric cross-sections, Bermuda area.	1	13 3/4	23 1/2	$0.50
30	Cross-section of Bermuda Seismograph Station.	1	18 1/4	26 1/2	0.50
31	Chart showing correlations between weather-conditions, rate of tilt, and microseismic activity at Bermuda.	1	20 3/4	54	1.50
32	Map showing position of Bermuda relative to Mid-Atlantic Seismic Zone.	1	16 1/4	11 1/4	0.25
33	Isogonic map of Bermuda (1935).	1	9 5/8	18 1/8	0.25
34	Vertical-intensity magnetic map of St. George's, Bermuda.	1	17	20 3/4	0.25
35	Graphic illustration of shallow-water marine seismic technique	1	24	40 1/8	1.00
36	Graphic indication of moderate-depth marine seismic technique	1	27 3/4	40	1.25
37	Graphic indication of deep-sea seismic technique.	1	29 1/4	40 1/4	1.25
38	Chart indicating comparative depths at which marine seismic work is being done.	1	40 1/2	17 5/8	0.75
39	Diagram showing recording oscillograph as used in deep-sea seismic measurements.	1	40 1/4	26 3/4	1.00
40	Iso-anomaly map of Gulf-West Indian Region.	1	30 1/2	51 1/2	2.00
41	Map showing geophysical methods used in discovery of Texas and Louisiana Gulf Coast Oil-Fields	1	35	32	2.50
42	Map showing geophysical method used in discovery of oil-fields in Illinois Basin.	1	32 1/2	25 1/2	1.50
43	Basement-surface sections across United States.	1	19 1/2	58	1.25
44	Gravitational and basement-section across U.S.	1	35	32	2.00
45	Gravity-station map of U.S. (1939).	2	49 1/2	75	3.50
46	"Vertical-intensity" magnetic sections across Palisade Diabase (Sill).	1	45	39	2.00
47	Graph comparing oil-production and estimated reserves of oil and new fields, Illinois Basin, July, 1939.	1	20	11 1/4	0.25
48	Graph comparing oil-production and estimated reserves, Gulf Coast Region	1	18 1/2	42 3/4	0.75
49	"Vertical-intensity" magnetic section along Barnegat Bay traverse.	1	32	47 3/4	0.75
50	Model showing approximate configuration of surface of basement-complex in U.S.	Approx. 50 by 75 inches			....[c]

[a]The regular U.S. Geological Survey 1/2,500,000 geologic map of the United States was used as special exhibit 7 for comparison with exhibits 1-11.

[b]The New Jersey Geological Survey's regular 1/250,000 State map was used as special exhibit 16 for comparison with exhibits 17-21, etc.

[c]Quotations on reproductions of this model cannot be given until there is indication as to how many may wish copies.

APPENDIX E--REPORT OF SPECIAL COMMITTEE FOR COOPERATION WITH INTERNATIONAL COMMISSION FOR STUDY OF TIDAL WAVES

L. P. Disney, Chairman
P. Byerly H. N. Eaton W. F. McDonald

Effective cooperation with the International Commission has been restricted as a reulst of conditions in Europe.

A paper by P. Byerly on microseisms at Berkeley and surf on nearby coasts was forwarded to the Secretary for printing in the publication of the Commission, but no acknowledgment has been received.

Considerable data and material have been gathered on the hurricane of September 1938. In addition to records compiled from questionnaires sent out by the Committee, the following reports have been collected:

I. R. Tannehill, Hurricane of September 17 to 22, 1938, Mon. Weath. Rev., Sept. 1938, pp. 286-288 (for sale by Superintendent of Documents, Washington, D. C., price 20 cents).

The great hurricane and tidal wave--Rhode Island, September 21, 1938, published by the Providence Journal Company, 1938 (price 35 cents a copy).

Charles F. Brooks, Hurricanes into New England--Meteorology of the storm of September 21, 1938, Geogr. Rev., v. 29, pp. 119-127, 1939.

C. L. Hall, The 1938 hurricane and its effect on Long Island beach-protection structures, Civ. Eng., March 1939.

U. S. Engineer Office, Supplemental report on hurricane of September 21, 1938, and its effect on the coastal region, Providence, Rhode Island, June 1939.

Tidal wave in hurricane reached 17-foot height, Eng. News-Record, Sept. 28, 1939. (This is a short article summarizing data collected by the Tidal-Wave Committee of the American Geophysical Union.)

Massachusetts Geodetic Survey, High water data--Floods of March 1936 and September 1938 in Massachusetts, supplemented by Storm-tide hurricane of September 1938 in Massachusetts, 100 Nashua Street, Boston, 1939. (It is understood that this report sells for 40 cents.)

Consolidated Edison Company of New York, Inc., Research Report No. 163, Conditions surrounding the hurricane of September 21, 1938, Research Bureau, Department-Technical Development and Research, Aug. 4, 1939.

U. S. Coast and Geodetic Survey,
Washington, D. C.

APPENDIX I--REPORT OF THE SPECIAL FINANCE COMMITTEE

W. C. Lowdermilk, Chairman
L. H. Adams R. M. Field J. A. Fleming C. O. Iselin

Your Committee takes this opportunity to state its gratification for the rapid growth of the American Geophysical Union in response to needs for coordination and cooperation in research in the dynamics of Earth sciences. This welcomed growth, however, has brought on new problems to finance adequately a journal of the Union, and to relieve the increasing load on volunteer officers of the Union, especially on our General Secretary, who deserves the special thanks of the Union for his unstinted devotion of all his spare time to its interests. We must provide for sufficient assistance to carry on the work without imposing on our General Secretary.

The need--The enlarging demands will require, in the estimation of the Committee, the following proposed budget:

Budget needs for 1940-41		
Full-time clerical assistance	$1300	
Part-time clerical assistance	400	
Planographer for publication of transactions	4200	
Full-time services of an editor	3000	
Honoraria for eight associate editors--one for each Section	1200	
Stationery	400	
Postage and miscellaneous	700	
Expenses, annual and regional meetings	300	$11500
Funds in sight		
Dues from 1300 members at $3.00	$3900	
Sales of reprints and transactions	2600	6500
Amount to be provided		$ 5000

The problem--The task is to increase the income by $5000 per annum. Possible ways of doing this are:

(1) Increase the amount of annual dues
(2) Establish two grades of membership--Junior at $3.00 and Senior at $5.00
(3) Establish life-memberships at $100
(4) Establish organization and institutional membership with annual dues of $25
(5) Returns from advertising in the Transactions
(6) A drive to increase membership at the present dues
(7) Subsidies to the Transactions from Foundations and other sources

Recommendations--All these possibilities for increase of income have been considered; but time has not been available to explore all prospective means as fully as we would wish to do. However, the Special Finance Committee wishes to lay before the Executive Committee the following recommendations:

(1) It is recommended that the dues be retained at $3.00 per year without setting up two grades of Junior or Senior membership but that life-memberships be established at a minimum of $100.

(2) It is recommended that organization and institutional memberships be established with dues at $25 per annum and that for the present a library subscription-rate of $5.00 be established.

(3) It is recommended that proper steps be taken by individual Sections to bring advantages of membership before interested individuals, and that the methods be worked out in a conference of representatives of Sections of the Union.

(4) It is recommended, without prejudice to going activities, to consolidate into the Transactions, publications of Sections of the Union and to open the pages of the Transactions to approved advertising with details to be worked out by the Executive Committee.

(5) In view of the improbability of these means to make up the difference of $5000 within the current year, it is recommended that subsidies be sought to tide the publication of the Transactions through the coming year or preferably three years.

Washington, D. C.,
April 22, 1940

APPENDIX J-a--MINUTES OF THE ANNUAL MEETING, APRIL 25, 1940, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The meeting was held in the Lecture Room of the National Academy - Research Council Building, Washington, D. C., April 25, 1940. The meeting was called to order by the President, C. H. Swick, at 2:05 p.m. The registered attendance was 82 [see Appendix A].

The President called attention to the fact that the minutes of the Twentieth Annual Meeting held April 27, 1939, had been printed and sent out to the members and that no corrections had been received. The minutes were declared approved as printed and circulated.

The Secretary submitted a brief report [see Appendix J-a(1)] in regard to the participation of the Section of Geodesy in the General Assembly of the International Union of Geodesy and Geophysics, which was held in Washington in September 1939.

The President asked if the Committee on Relation of Inch and Meter had a report to make. Mr. L. V. Judson stated that the Committee had no report.

The President stated that no resolutions had been called to his attention and that no resolutions committee had been appointed.

The report of the Nominating Committee [W. D. Lambert and H. R. Morgan] was given by Mr. Lambert. W. D. Sutcliffe was nominated for Secretary for three years from July 1, 1940. No nominations were made from the floor, and a motion was made, seconded, and passed that the nominations be closed and that a unanimous ballot be cast for Mr. Sutcliffe.

The Section then proceeded to hear and discuss the ten papers on the scientific program as published in these Transactions. There being no further business, the meeting adjourned at 5:09 p.m.

(Signed) Walter D. Sutcliffe, Secretary,
Section of Geodesy

APPENDIX J-a(1)--REPORT OF THE SECRETARY TO THE TWENTY-FIRST ANNUAL MEETING OF THE SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION, APRIL 25, 1940

In September, 1939, the Seventh General Assembly of the International Union of Geodesy and Geophysics was held in Washington, D. C. The International Association of Geodesy held several meetings, and the officers and members of the Section of Geodesy, American Geophysical Union, assisted in the preparations for these meetings and took an active part in them. The Executive Committee of the Section of Geodesy appointed the Secretary of the Section to act as Local Secre-

tary for the International Association of Geodesy, in which capacity he acted as liaison officer to the Secretary of the International Association and served on the Committee of Local Secretaries.

The President of the International Association of Geodesy, Dr. F. A. Vening Meinesz, of the Netherlands, came to Washington and remained to preside over all the meetings of the Association, although the other delegates from the Netherlands returned home as soon as war was declared. The presence of Dr. Vening Meinesz did much to make the meetings of the Association successful.

The Secretary of the International Association of Geodesy, General G. Perrier, of France, came to Washington several days before the meetings were scheduled to begin but returned to France immediately with all the other French delegates as soon as war was declared. W. D. Lambert was selected to act as Secretary in place of General Perrier, and H. S. Jelstrup and W. D. Sutcliffe were chosen as Assistant Secretaries. C. L. Garner and C. H. Swick were appointed acting Vice-Presidents of the Association.

It was necessary to greatly revise the printed programs for the meetings of the Association of Geodesy. Because of the absence of many delegates and members of committees, most of the committee meetings were eliminated and instead plenary sessions were held. Each section was devoted to a single subject under the leadership of someone well acquainted with the subject. The following members of the Section of Geodesy acted as leaders of plenary sessions: C. L. Garner, C. H. Swick, H. S. Rappleye, and C. J. Clifford.

Other members of the Section of Geodesy served on important committees: R. M. Field was Chairman and William Bowie was Vice-Chairman of the Finance Committee; C. L. Garner was Chairman and H. S. Rappleye was Vice-Chairman of the Entertainment Committee; C. R. Longwell was Chairman of the Committee on Coordinated Interests; W. T. Thom, Jr., was Chairman of the Travel Committee; H. T. Stetson, was Chairman of the Publicity Committee; L. V. Judson was Vice-Chairman of the Committee on Exhibits. William Bowie acted as General Secretary of the International Union in place of Brigadier Winterbotham, who returned to England as soon as war was declared, and he also delivered Winterbotham's lecture on "Geodesy and mapping in the British Empire."

Several excursions were arranged for the Association of Geodesy. One afternoon was spent at the Latitude Observatory at Gaithersburg where a field gravity-party of the Coast and Geodetic Survey was seen in operation as well as the Observatory. Another afternoon was spent at Lewistown, Maryland, where a triangulation-party of the Coast and Geodetic Survey was at work and a steel observation-tower was erected over a triangulation-station. A third excursion was to Chevy Chase Lake to see a leveling party of the Coast and Geodetic Survey.

The following members of the Section of Geodesy were designated by the National Research Council and National Academy of Sciences to act as official delegates at the Washington Assembly of the International Union of Geodesy and Geophysics: William Bowie, E. A. Eckhardt, R. M. Field, C. L. Garner, W. D. Lambert, C. R. Longwell, J. B. Macelwane, H. T. Stetson, W. D. Sutcliffe, C. H. Swick, W. T. Thom, Jr., and R. M. Wilson. In addition to the above, all members of the Section who attended the Assembly and paid registration fees were designated as delegates.

(Signed) Walter D. Sutcliffe, Secretary,
Section of Geodesy

APPENDIX J-b--MINUTES OF THE ANNUAL MEETING, APRIL 25, 1940, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The meeting was called to order by the President. Rev. Dr. J. B. Macelwane, S.J., at 2:00 p.m. in the Library of the National Academy - Research Council Building, Washington, D. C. Forty-five persons registered their attendance [see Appendix A].

The eleven scientific papers and six progress-reports presented are printed in these Transactions.

In the absence of the authors, Rev. Linehan's paper was read by the Secretary, while those of Messrs. Birkenhauer and Walter were presented by the President. Following the discussion of Rev. Linehan's paper, the importance of data from stations in the Atlantic Basin was emphasized and a resolution was adopted and referred to the Union's Committee on Resolutions. [This is resolution (3) given in the minutes of the General Assembly of the Union.]

There was lively discussion of all the papers on the program, especially from those interested in crustal structure. This was particularly true of the papers by the President of the Union, Professor R. M. Field, and the President of the International Association of Seismology, Captain N. H. Heck.

At the close of the meeting the Secretary gave a brief résumé of the status of the work of the International Association of Seismology, especially as it concerned the material of the Seventh Assembly intended for publication. He reported that the Proceedings had been forwarded to Professor Rothé, the General Secretary of the Association, and that the various papers presented were being forwarded in partial shipments, at Professor Rothé's request, for early publication. Some interesting extracts from Professor Rothé's letters were quoted to show how, after considerable personal hardship, he had successfully overcome a number of serious problems arising from the unsettled European situation.

The meeting adjourned at 5:15 p.m.

(Signed) Frank Neumann, Secretary,
Section of Seismology

APPENDIX J-c--MINUTES OF THE ANNUAL MEETING, APRIL 25, 1940, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The twenty-first annual meeting of the Section of Meteorology, Vice-President Thornthwaite presiding in place of President Weightman who was absent from Washington, was held from 9:15 a.m. to 12:30 p.m., April 25, 1940, in the Lecture Room of the National Academy - Research Council Building, Washington, D. C. One hundred members and guests registered their attendance [see Appendix A], but the actual number present was considerably in excess of this as many did not register.

The reading of the minutes of the previous meeting was dispensed with as they had already been published in the Transactions of 1939 and no corrections had been received.

There being no further business, the scientific program was presented including the papers printed in these Transactions.

(Signed) H. D. Harradon, Secretary,
Section of Meteorology

APPENDIX J-d--MINUTES OF THE ANNUAL MEETING, APRIL 24, 1940, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The twenty-first annual meeting of the Section of Terrestrial Magnetism and Electricity was held April 24, 1940, in the Auditorium of the United States National Museum in Washington, D. C. President E. O. Hulburt called the meeting to order at 9:10 a.m. The registered attendance was 75 [see Appendix A].

The report of the Secretary was read and approved [see Appendix J-d(1)]. There being no further business, the Section proceeded to the scientific program and the papers published in these Transactions were presented. The papers by Woollard and Roman were read by title. Richardson's paper was presented by Hulburt. A communication from R. F. Ewald of the Aluminum Company of America was read, calling attention to a map recently published in Life, showing regions of greatest earth-current activity during recent magnetic storms and pointing out their correlation with areas of pre-Cambrian rocks. The matter is being considered by geologists at the Massachusetts Institute of Technology.

The meeting adjourned at 11:55 a.m.

(Signed) J. W. Joyce, Secretary,
Section of Terrestrial Magnetism
and Electricity

APPENDIX J-d(1)--REPORT OF THE SECRETARY TO THE TWENTY-FIRST ANNUAL MEETING OF THE SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

No special meetings of the Section have been held during the year. The minutes of the twentieth annual meeting were published in the Transactions of 1939, and no additions or corrections have been received.

The Seventh Assembly of the International Union of Geodesy and Geophysics was held in Washington, D. C., September 4-15, 1939. Despite conditions abroad which prevented many of the European delegates from attending, the Assembly was one of the most successful yet held from the standpoint of scientific accomplishments. It was decided by the Executive Committee to postpone all administrative matters, proposed new statutes, the inauguration of new projects for which funds were not already available, and the election of new officers and a new Executive Committee. All officers and the Executive Committee of the Union were therefore continued until the next General Assembly, or until such time as the Executive Committee may decide. The elimination of these matters, which are usually time-consuming, left the entire Assembly for the discussion of scientific matters and full advantage was taken of this fact. Fortunately, the various associations found it possible to continue many of the important international enterprises, either in their original or a modified form, with funds still available.

The Association of Terrestrial Magnetism and Electricity held ten meetings, of which one was a joint meeting with the Commission on Continental and Oceanic Structure and two were joint meetings with the Association of Meteorology. The average attendance ranged from 33 to 75. In addition, two meeting-periods were scheduled for attendance at the presidential addresses of the Association of Seismology and of the Association of Meteorology. Over 100 reports and scientific papers were submitted, almost all prepared especially for this Assembly in printed, planographed, or multigraphed form for distribution to all interested delegates and guests.

Two outstanding features of the meetings were the symposium on instruments led by the Danish delegates and the two symposia at the joint meetings with the Association of Meteorology on (1) thunder-storms and the electricity of the lower atmosphere and (2) upper atmospheric physics including meteorological and magnetic aspects of solar and terrestrial relationships. Other scientific aspects which received more than usual attention were those concerned with the characterization of magnetic activity and the adoption of a three-hour-range index in addition to the long-continued magnetic character-figures on the scale of 0, 1, and 2. This new index promises to be of great value in correlative studies particularly as regards ionospheric phenomena.

Nine of the ten committees were reappointed and in some cases additional members were added. The two joint committees of the Association (1) with the Commission of Terrestrial Magnetism and Atmospheric Electricity of the International Meteorological Organization and (2) with the International Scientific Radio Union were recommended for continuation to these bodies. Three new committees were formed: (1) On Ionic Equilibrium, (2) On Observational Technique, and (3) On Three-Hour-Range Index for Magnetic Characterization. Chapman was continued as reporter on international collaboration for promoting study of the influence of the Moon on geophysical phenomena.

A total of 12 resolutions embodying results of important discussions were passed by the Association. These are given in the detailed account of the Assembly published in the December 1939 issue of the Journal of Terrestrial Magnetism and Atmospheric Electricity [v. 44, pp. 471-479].

Attention is called to a correction to resolution No. 4 as published. It should read as follows:

(4) Control of variometers and absolute instruments--(a) The Association reaffirms its Resolution 3 adopted at the Edinburgh Assembly of the great need of examination at regular intervals, at least every two years, of magnetic instruments, including the control of the direction of the magnetic axes of the magnets in variometers.

(b) The Association recommends that instruments used for the determination of declination and inclination are adjusted so that their corrections do not exceed the standard error of a single determination.

Of the 12 resolutions, one was felt to be of sufficient importance to warrant the support of the entire Union. This resolution, recommended by the Association and unanimously adopted by the Union at its final session, was as follows:

The International Union of Geodesy and Geophysics strongly recommends that governments interested in the magnetic survey of the oceans make provision for the building of non-magnetic vessels to continue accurate geomagnetic determinations at sea.

On February 1, 1940, the daily "three-hour-range" indices from Cheltenham were added to the Ursigram messages, and on April 1, 1940, the seven American-operated magnetic observatories began the assignment of K-figures. These data are published each week in the Science Service Research Aid Announcement, along with the American magnetic character-figures derived from reports from the same seven observatories.

The preliminary notice of the twenty-first annual meeting was distributed by the General Secretary of the Union under date of March 8, 1940.

Progress-reports received from the United States Coast and Geodetic Survey, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and the National Bureau of Standards are included in the Transactions of 1940.

The membership of the Section, now nearly 250, shows an increase of about five per cent over last year.

(Signed) J. W. Joyce, Secretary,
Section of Terrestrial Magnetism
and Electricity

APPENDIX J-e--MINUTES OF THE ANNUAL MEETING, APRIL 26, 1940, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The annual meeting of the Section of Oceanography was held at Washington, D. C., April 26, 1940, in the Library of the National Academy - Research Council Building. The meeting was called to order by President C. O'D. Iselin at 9:08 a.m. Some 80 members and guests registered attendance [see Appendix A].

The minutes of the previous meeting, having been distributed to the members and there being no corrections or additions, were approved.

Eight scientific papers were presented; these are printed in the Transactions of 1940. Admiral Waesche's paper was presented by Commander E. H. Smith of the United States Coast Guard. The paper presented by Admiral Colbert was discussed by Commander E. H. Smith and Dr. C. O'D. Iselin. Dr. Sverdrup's paper was read by Dr. T. Wayland Vaughan. The paper presented by Dr. H. H. Hess was discussed by Dr. Vaughan. Mr. H. R. Seiwell's paper was discussed by Commander Borden, Dr. Arctowski, Dr. Trask, and Dr. Iselin.

The meeting adjourned at 11:40 a.m.

(Signed) Paul A. Smith, Acting Secretary,
Section of Oceanography

APPENDIX J-f--MINUTES OF THE ANNUAL MEETING, APRIL 24, 1940, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The annual meeting of the Section of Volcanology was called to order at 2:00 p.m., April 24, 1940, by Vice-President A.Knopf (in the absence of the President of the Section, E. G. Zies) in Room 42 of the National Museum, Washington, D. C. After the second paper the meeting was moved to the Auditorium because of the crowding of Room 42. Eighty-seven members and guests registered attendance [see Appendix A].

The reading of the minutes of the previous annual meeting was dispensed with, as the minutes ahd been published in the Transactions of 1939.

The scientific papers were presented as published in the Transactions of 1940 and were discussed.

After the scientific session the Nominating Committee presented the name of Earl Ingerson for Secretary of the Section to fill the vacancy occasioned by the resignation of James Gilluly.

No other nominations were made and the report of the Nominating Committee was accepted. The term expires June 30, 1941.

(Signed) Earl Ingerson, Secretary,
Section of Volcanology

APPENDIX J-g--MINUTES OF THE ANNUAL MEETING, APRIL 25-27, 1940, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

The Section of Hydrology held three sessions in the National Academy - Research Council Building on April 25 and 26, 1940, a round-table discussion in the North Building, Department of the Interior, on April 27, and a joint meeting with the Pick and Hammer Club on the evening of April 26 at the Lido Restaurant.

The first session was called to order at 9:10 a.m., April 25, in the Auditorium by President Grover. Nine papers and five reports of research committees were presented. One hundred and one members and guests were present. The session adjourned at 12:45 p.m.

The second session was called to order at 2:00 p.m., April 25, in the Auditorium by President Grover. The minutes of the annual meeting of 1939, as published in the Transactions of 1939 [part III, pp. 480-482], were approved. A resolution on the collection and study of hydrologic data, presented by G. W. Musgrave, was adopted. [This is resolution (5) given in the minutes of the General Assembly of the Union.] Thirteen papers and the reports of three research committees were presented. Seventy-five members and guests were present. The session adjourned at 5:15 p.m.

The third session was called to order at 9:15 a.m., April 26, in the Auditorium by President Grover. Sixteen papers and the reports of five research committees were presented. Eighty-five members and guests were present. The session adjourned at 12:00 noon.

The round-table conference was called to order at 9:00 a.m., April 27, in Room 5243 by the leader, W. G. Hoyt. The general subjects of runoff and infiltration, and their correlation, were discussed until late in the afternoon with an intermission for lunch. Seventy members and guests were present.

The informal joint meeting with the Pick and Hammer Club was held at 8:00 p.m., April 26, at the Lido Restaurant. Two papers on the movement and hydraulics of ground-water were presented, which were followed by lively discussion. The attendance was about eighty.

The total registration of members and guests at the regular sessions and the round-table conference was 174 [see Appendix A].

(Signed) K. Hilding Beij, Secretary,
Section of Hydrology

APPENDIX J-h--MINUTES OF THE FIRST MEETING OF THE SECTION OF TECTONOPHYSICS, APRIL 25, 1940, AMERICAN GEOPHYSICAL UNION

The meeting was called to order in the Library of the National Academy - Research Council Building at 9:00 a.m., April 25, 1940, by the President of the Union, Dr. Richard M. Field. In opening the meeting, Dr. Field stated the wide-spread desire of members of the Union to elicit discussions on problems of earth deformation which are not treated in the other sections of the Union, and described how this had resulted in the formation of a new section of the Union. The story was told of how the name of the new section "Tectonophysics" was coined by Dr. N. L. Bowen one afternoon on the steps of the National Academy - Research Council Building when posed by the problem of how to designate this new borderland field between geophysics, physics, and geology, which deals with the application of physical methods, geologic and geophysical data to the solution of problems of tectonics.

The first business of the Section was the election of officers. The Nominating Committee, composed of W. T. Thom, Jr., Maurice Ewing, H. T. Stetson, R. M. Field, and J. A. Fleming, presented a slate of officers who were elected unanimously for the term ending June 30, 1943. These are as follows: President, Leason H. Adams; Vice-President, R. A. Daly; Secretary, David Griggs. Dr. Field then turned the meeting over to the newly elected officers.

The scientific session of the Section was composed of the five papers as printed in these Transactions, which were discussed by the following, respectively: T. S. Lovering, E. B. Knopf, and A. C. Lane; Leonard Obert and T. S. Lovering; L. H. Adams, A. C. Lane, and W. W. Rubey; H. F. Reid, Arthur Keith, A. Nadai, E. B. Knopf, and M. K. Hubbert; D. T. Griggs and M. K. Hubbert.

The meeting adjourned at 12:15 p.m.

To date 301 members of the Union are affiliated with the Section of Tectonophysics; 78 of these attended the meeting [see Appendix A].

(Signed) David Griggs, Secretary,
Section of Tectonophysics

ADDENDUM TO REPORT OF COMMITTEE ON SNOW, 1939-40—LIST OF CURRENT PUBLICATIONS ON SNOW AND ICE

Carl Elges

The following list of current publications on snow and ice has been assembled by the compiler with assistance of others who have generously provided articles and reports.

The list of latest papers and books of Soviet cryologists on ice and snow was submitted by Professor B. P. Weinberg to the International Commission of Snow, but, because of uncertainty regarding publication of the International Bibliography, it is included as an appendix to the list of current publications which itself is world-wide. Because of geographical interest, the list by Professor Weinberg has been kept as a unit. Furthermore, the compiler's arrangement by authors has been retained.

GENERAL

C. G. Abbot, Weather predictions two weeks ahead now practicable (abstract), Heat. and Ven., v. 36, p. 63, May 1939.

David I. Blumenstock, Rainfall characteristics as related to soil erosion, U. S. Dept. Agric., Tech. Bull. No. 698, 44 pp., December 1939.

Francis W. Dunmore, An improved electric hygrometer, J. Res., Nation. Bur. Stand., pp. 701-714, December 1939.

W. Findeisen, Zur Frage der Regentropfenbildung in reinen Wasserwolken, Met. Zs., Bd. 56, Heft 10, pp. 365-368, October 1939.

E. Huntington, Medical climatology, by C. A. Mills, Rev. Sci., v. 90, pp. 540-542, December 8, 1939.

F. Löhle, Wetterzeichen und Wettervorhersage, Met. Zs., Bd. 56, Heft 10, pp. 383-387, October 1939.

R. L. Parshall, Analysis of fifty years' record of meteorological data taken at the Colorado Experiment Station, Fort Collins, Colorado, Colo. Agric. Exp. Bull. No. 456, pp. 1-16, 1939.

Report of cooperative hydrologic investigations, Penn. Dept. For. and Waters, U. S. Wea. Bur. and Geol. Surv., Commonwealth of Penn., August 1939.

W. A. Sommerfield, Weather and your health, Hygeia, v. 17, pp. 1114-1116, December 1939.

George F. Taylor, The influence of topography on weather forecasting at Salt Lake City, Utah, J. Aeron. Sci., pp. 18-21, November 1939.

Weather; Norwegians found the third dimension, the airlines commercialized it, and the U. S. Weather Bureau eventually caught on, Fortune, v. 21, pp. 58-68+, April 1940.

SNOW

(1) General

Henry I. Baldwin, Some observations on snow-reports in New England, Trans. Amer. Geophys. Union, Part II, pp. 726-728, 1938.

J. Barloti, Snow layer in Latvia, 1921-1931, State Met. Bur. Latvia, 33 pp., Riga, 1932.

Joachim Blüthgen, Die landschaftliche Bedeutung des Schnees, Zs. angew. Met., pp. 111-122, April 1939.

L. Bonacina, The snowfalls of December and January, Met. Mag., v. 74, p. 48, 1939.

A. J. Bull, Nivation in the South Downs, Papers and Discussions, Assn. Study Snow and Ice, v. 1, No. 1, pp. 1-3 and 21-22, January and September 1939.

J. E. Church, Annual report of the Committee on Snow, 1937-38, Trans. Amer. Geophys. Union, Part I, pp. 281-314, 1938.

C. Douglas, Frost and snow in December and January, Met. Mag., v. 74, p. 12, 1939.

E. Eugster, Schneestudien im Oberwallis und ihre Anwendung auf den Lawinenverbau, Promotionsarbeit, Eidg. Tech. Hochschule, Zürich, 1938.

R. Haefeli, Ueber die Tätigkeit der Station Weissfluhjoch der Schweiz: Kommission für Schnee und Lawinen-forschung, Schweizer. Bauzeitung, v. 113, 1939.

D. Haig-Thomas, Tracks in the snow, Hodder and Stoughton, 1939.

E. Hawke, The winter's snowfall in the Chiltern Hills, Met. Mag., v. 74, p. 113, 1939.

W. V. Lewis, Snow patch erosion in Ireland, Geog. J., v. 64, p. 153, 1939.

G. Manley, On the occurrence of snow-cover in Great Britain, Quart. J. R. Met. Soc., v. 65, p. 2, 1939.

François E. Matthes, The new International Commission of Snow and Glaciers, Science, v. 91, pp. 317-318, March 29, 1940.

G. D. Matthews, Snow utilization in prairie agriculture, Dominion Canada, Dept. Agric., Pub. 696, May 1940.

R. L. Nichols, Nieves penitentes near Boston, Massachusetts; pinnacle forms, Science, v. 89, pp. 557-558, June 16, 1939.

SNOW--Continued

(1) General--Concluded

W. Paulcke, Praktischer Schnee-und Lawinenkunde, J. Springer, Berlin, 1938, 218 pp., v. 38 of series Verständliche Wissenschaft. (Summary by R. G. Stone, Bull. Amer. Met. Soc., v. 20, pp. 408-409, November 1939.)

J. B. Priestley, First snow, Readers Digest, v. 35, p. 81, December 1939.

Public enemy number zero, Pop. Mech., v. 72, pp. 866-869+, December 1939.

Robert G. Stone, The distribution of the average depth of snow on ground in New York and New England, Trans. Amer. Geophys. Union, Part I, pp. 486-492, 1938.

(2) Precipitation and evaporation

Merrill Bernard, The expanded program of the United States Weather Bureau in snow-work, Trans. Amer. Geophys. Union, Part II, pp. 673-685, 1938.

T. Maeda, The effect of wind velocity on the measurement of rainfall by rain-gages, J. Met. Soc. Japan, pp. 26-31, January 1940.

P. L. Mercanton, Recherches de technique pluviometrique, Ann. Schweizerishen Met. Zentralanstalt, 8 pp., 1939.

H. G. Wilm, A. Z. Nelson, and H. C. Storey, An analysis of precipitation measurements on mountain watersheds, Mon. Wea. Rev., pp. 168-172, June 1939.

(3) Snow-surveying

George D. Clyde, Cost and benefits of snow-surveying in Utah, Trans. Amer. Geophys. Union, Part II, pp. 707-711, 1938.

George G. Devore, Value of snow-surveying in the Tahoe-Truckee Basin, Trans. Amer. Geophys. Union, Part II, pp. 705-706, 1938.

G. Manley, Report on the snow survey of the British hills, Papers and Discussions, Assn. Study Snow and Ice, v. 1, pp. 18-20, September 1939.

J. C. Marr, Snow surveying. U. S. Dept. Agric., Misc. Pub. No. 380, June 1940.

James C. Marr and Paul A. Ewing, Snow surveying, Soil Conservation, v. 5, pp. 144-147, December 1939.

Fred H. Paget, Development of snow-surveying in California, Trans. Amer. Geophys. Union, Part II, pp. 686-689, 1938.

J. E. Phillips, Economic value of snow-surveying for the Los Angeles Aqueduct, Trans. Amer. Geophys. Union, Part II, pp. 706-707, 1938.

Snowmen, Amer. Mag., v. 129, pp. 116-117, February 1940.

Summary of snow survey measurements in Oregon, 1926-1940, inclusive, Div. Irr., Soil Conservation Serv., and Oregon State Eng. cooperating, June 30, 1940.

(4) Forecasting

H. P. Boardman, George G. Devore, and Leigh Sanford, Seasonal snow-survey and forecast of the stream-flow in Central Sierra Quadrangle, Nev. Coop. Snow-Surveys, April 1940.

D. Champion, Snow fall and stream flow, Met. Mag., v. 74, p. 20, 1939.

George D. Clyde, Utah cooperative snow-surveys and water-supply forecasts, Utah Agric. Exp. Sta. Mimeo. Sheet, 226, April 1, 1940.

Carl Elges and J. E. Church, Seasonal snow-survey and forecast of stream-flow in Humboldt Quadrangle, Federal-State Coop. Snow-Surveys, Reno, Nev., April 1, 1940.

Richard C. Farrow, Establishing first-year normals on the basis of accumulated snowfall and some forecasts from runoff-ratios, Trans. Amer. Geophys. Union, Part II, pp. 689-695, 1938.

F. B. Groissmayr, Experimental forecasting of the severe 1935/36 winter and the hot droughty summer which followed it in Central U.S.A., Bull. Amer. Met. Soc., v. 20, pp. 191-192, May 1939.

Robert Leaver, Winter precipitation versus snow-survey for forecasting on Skagit River, Washington, Trans. Amer. Geophys. Union, Part II, pp. 695-702, 1938.

W. W. McLaughlin, Factors affecting run-off forecasts based on snow surveys, Soil Conservation, v. 5, pp. 148-151, 163, December 1939.

R. L. Parshall, Snow surveys permit forecasts of water, Colo. Agric. Exp. Farm Bull., v. 1, p. 16, April 1939.

Snow-surveys and irrigation-forecasts for Oregon, Div. Irr., Soil Conservation Serv. and Oregon State Eng. cooperating, Bull., February 1, March 1, and April 1, 1940.

Snow-surveys and irrigation-water forecasts for Colorado River Basin, Div. Irr., Soil Conservation Serv., in cooperation with State Dept., April 1 and May 1, 1940.

Snow-surveys and irrigation-water forecasts for Columbia River Basin and other drainage-areas in Oregon and Washington, Div. Irr., Soil Conservation Serv., in cooperation with States, March 1, April 1, and May 1, 1940.

Snow-surveys and irrigation-water forecasts for Missouri and Arkansas River basins, Div. Irr., Soil Conservation Serv., in cooperation with State Dept., April 1 and May 1, 1940.

Snow-surveys and irrigation-water forecasts for Rio Grande Basin, Div. Irr., Soil Conservation Serv., in cooperation with State Dept., April 1 and May 1, 1940.

SNOW--Continued

(4) Forecasting--Concluded

Snow-surveys and precipitation-data and seasonal forecast of stream-flow, Cal. Coop. Snow Surv., April 1, 1940 (a bulletin of snow-conditions and precipitation was released on January 1, February 1, March 1, and May 1, 1940).

H. C. Willett, Certain statistical relationships bearing on the preparation of five-day weather forecasts in the United States, Bull. Amer. Met. Soc., v. 20, pp. 329-331, October 1939.

(5) Normals and trends

H. P. Gillette, Dry years ahead; study of varves and rainfall cycles, Roads and Streets, v. 82, pp. 76, 78, May 1939.

Halbert P. Gillette, Varves and rock strata as recorders of cycles, Bull. Amer. Met. Soc., v. 21, pp. 33-36, January 1940.

H. P. Gillette, Varves and rock strata as recorders of cycles, Roads and Streets, v. 82, pp. 38-40, 42, July 1939.

W. Gorczynski, The aridity coefficient and its application to California, Mimeo., Scripps Inst. Oceanogr., La Jolla, California.

Ocean currents forecast the weather, Pop. Mech., v. 73, pp. 408-410+, March 1940.

I. I. Schell, Long-range weather forecasting; its present status and future possibilities, Heating-Piping, v. 11, pp. 285-287, May 1939.

Tree rings fallible as records of weather, Science News-Letter, v. 37, p. 29, January 13, 1940.

(6) Runoff-factors

R. W. Baird, Watershed and hydrologic studies on the Blacklands Experimental Watershed, Agric. Eng., v. 20, pp. 273-276, July 1939.

G. J. Boyoucos and A. H. Mick, An electrical resistance method for the continuous measurement of soil moisture under field conditions, Mich. Agric. Exp. Sta., Tech. Bull. 172, April 1940.

E. F. Brater, Unit hydrograph principle applied to small water-sheds, Amer. Soc. Civ. Eng., Proc., v. 65, pp. 1191-1215, September 1939.

C. K. Cooperrider and G. G. Sykes, Relationship of stream flow to precipitation on the Salt River Watershed above Roosevelt Dam, Ariz. Agric. Exp. Tech. Bull. No. 76, pp. 1-69, 1938.

G. W. Craddock, Forestry and water, J. For., v. 38, pp. 141-146, February 1940.

C. H. Diebold, The effect of vegetation upon snow cover and frost penetration during the March 1936 floods, J. For., v. 36, pp. 1131-1137, 1938.

J. Girand, Water supply on upper Salt River, Arizona, Amer. Soc. Civ. Eng., Proc., v. 65, pp. 1675-1686, December 1939.

Richard A. Hertzler, Engineering aspects of the influence of forests on mountain streams, Civ. Eng., v. 9, pp. 487-489, August 1939.

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B. P. Weinberg

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Tbilisskij Nauchno-Issledovatelskij Institut Soorujhenij -- Tbilisi Science Research Institute of Construction
Tekhnicheskaja Entsiklopedia -- Technical Encyclopedia
Transportnoe Stroiteljstvo -- Transport-Construction
Trudy Dalnevostochnoj Kompleksnoj Expedicii -- Transactions of the Far-East Complex (General Science) Expedition
Trudy Geographo-Ekonomicheskogo Nauchno-Issledovatelskogo Instituta -- Transactions of the Geographical-Economical Scientific Research Institute
Trudy I. Vsesojuznogo Sjezda Hydronito -- Transactions of First All-Union Congress of Engineering Technical Societies of Hydraulic Engineers
Trudy Leningradskogo Otdelenija Vsesojuznogo Nauchnogo i Ingenierno-Tekhnicheskogo Obshchestva Vodnogo Transporta -- Transactions of the Leningrad Section of All-Union Society of Science and Engineering Technology
Trudy Moskovskogo Instituta Inzhenerov Transporta -- Transactions of the Moscow Institute of Transport Engineers
Trudy Nauchno-Issledovatelskogo Instituta Puti NKPS -- Transactions of the Scientific Research Institute of the Peoples' Commissariat for Railway Communications

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Trudy Sredne-Aziatskogo Nauchno-Issledovateljskogo Instituta Irrigacii: Irrigacia i hydrotekhnika -- Transactions of the Middle-Asia Scientific Research Institute of Irrigation: Irrigation and hydrotechniques
Trudy Taimyrskoj Hydrograficheskoj Ekspedicii -- Transactions of the Taimyr Hydrographic Expedition
Trudy Uraljskogo Nauchno-Issledovateljskogo Lesopromyshlennogo Instituta -- Transactions of Ural Scientific Research Institute of Forest-Industry

Uchenye Zapiski Moskovskogo Gosudarstvennogo Universiteta -- Scientific Memoirs of Moscow State University
Uspekhi Fizicheskikh Nauk -- Advances in Physical Sciences

Vestnik Edinoj Hydrometslujhby -- Messenger of United Hydrometeorological Service
Vestnik Inzhenerov i Tekhnikov -- Messenger of Engineers and Technicians
Vestnik Vozdushnago Flota -- Messenger of the Air-Fleet
Vestnik Znanija -- Messenger of Knowledge
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Za industrializaciju Sovetskogo Vostoka -- For Industrialization of the Soviet East
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Zoologicheskij Jhurnal -- Zoological Journal

Central Physical Observatory,
Leningrad, U.S.S.R.

[Editorial note: It was not possible to have Professor Weinberg read proof of the above list before publication. However, the original manuscript was carefully edited before the master-copy was prepared and proofs of the master-copy were carefully compared with the original both at Washington and at Reno, Nevada (by Dr. Church and his assistants). For valuable assistance for improvement of the English forms of titles and references we are indebted to Professor G. Gamow of George Washington University.

The chief difficulty is in the interchange of the letters i and j and v and w, which appears normal to the Russian way of spelling, possibly because of the difference in alphabet. Thus in [16] the letter I may more properly be J, in [331] the letters V.I. may be W.J., in [335] the letter V may be W, while in [585] and [622] "naledj" may be more properly "nadeli" as in [631], [651], and [654]. Note also "Dnjepr" and "Dniepr" in [452] and [453]. In [42] and [438] the designation "Swirj River" may better be "Svir River" as in [433]. In [279] author may be as in [278] and in [346] as in [345]. In some cases the second initial of author should perhaps be included but copy was followed, for example: [157] and [158]; [272], [274], and [275]; [466] and [467]; [640], [641], [642], and [643]; [652] and [653].

The following corrections are required: In [90] read "tractor-train" for "traction-train"; in [200] read "ice-currents" for "ice-current"; in [572] add before parenthesis at end ", 1939"; in [631] read "it" instead of "them"; in [646] read "hydrolaccoliths" instead of "hydrolaccolithes".]

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AMERICAN GEOPHYSICAL UNION

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(B and C) REPORTS AND PAPERS
WESTERN INTERSTATE SNOW-SURVEY CONFERENCE
AND SECTION OF HYDROLOGY
(NORTH PACIFIC COAST AND NORTH CONTINENTAL DIVIDE AREAS)

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.
SEPTEMBER, 1940

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AMERICAN GEOPHYSICAL UNION

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SYMPOSIUM

THE SURFACE AND SUBSURFACE
EXPLORATION OF CONTINENTAL BORDERS

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SYMPOSIUM

THE SURFACE AND SUBSURFACE EXPLORATION OF CONTINENTAL BORDERS

[A symposium presented at the invitation of Section E of the American Association for the Advancement of Science, by the American Geophysical Union, before a joint meeting of Sections D and E of the American Association for the Advancement of Science at Richmond, Virginia, December 27, 1938]

INTRODUCTION

The purpose of the symposium was to demonstrate that geophysical and geological science now possesses the experience and the technical appliances essential to the answering of two major questions in Earth science, namely:

(1) Are continents and ocean-basins really "permanent"--as has been widely held?

(2) Does major thrusting and crumpling in the Earth's crust result from "Continental drift" or from a relative lateral shifting of parts of the crust, under conditions of compression?

Both of these problems come to a focus in continental border areas. To solve either of them, we need to know: (1) whether old continental erosion-surfaces lie submerged (and buried) beneath present suboceanic areas; (2) whether the continents have sharp boundaries (like those of ice-cakes floating in a different, heavier, and more mobile material), or whether the subcontinental crust is essentially continuous with that underlying the ocean-basins; and (3) whether the deformational features (and consequently indicated strength-properties) of continents differ in any significant ways from those of the oceanic regions.

In order to indicate the present availability of all of the research experience and equipment needed for obtaining evidence from "continental-border" areas, Professor Longwell's introductory paper, indicative of the relative rôles of geology and geophysics in the determination of crustal structure, was followed by one by Doctor Veatch and Lieutenant Smith designed to show how modern submarine topographic surveying methods can reveal the presence of formerly emergent land-surfaces, which now lie deeply submerged beneath the ocean. Professor Nelson next described the age and origin of the former continental surface which now slopes seaward beneath the cover of the Atlantic Coastal Plain sediments, and Professor Ewing showed how this buried land-surface has been traced seaward to and beyond the present shore-line. Mr. Swick and Doctor Woollard, respectively, discussed how variations in the Earth's gravitational field are being measured, and how such variations have interpretable correlations with deep-seated crustal composition and structure. Professor Byerly then described how earthquake-records are being used to determine major crustal structure in the Pacific Coast Region, after which Doctor Stetson discussed how methods for the astronomic determination of time may be employed as checks and guides in the study of the differential lateral movements which recurrently take place within the Earth's crust.

RELATIVE RÔLES OF GEOLOGY AND GEOPHYSICS IN DETERMINATION OF CRUSTAL STRUCTURE

Chester R. Longwell

It is by no means an uncommon viewpoint that geology and geophysics are independent fields of science, and that students of the two fields have been driven to form a working alliance for the sake of mutual aid in attaining their respective goals. There is considerable basis for this view, illogical as it may appear. Although a large part of geology is nothing more nor less than the physics of the Earth, the term geophysics has become attached by usage to those aspects of Earth-science whose study involves the technique of mathematical physics. Many geologists have sufficient acquaintance with the technique to appreciate its value, but not enough to use it with facility. Similarly, many geophysicists have some general knowledge of geology, but do not pretend to be qualified geologists. A small but increasing number of men, who are at home in both subjects, recognizes most fully that geology and geophysics are equally indispensable parts of one general field of endeavor.

Developments during the past few years in the study of structural features have brought clearly into focus the interdependence between the two subjects. However, geologists appear to differ considerably in their appraisal of the rôle played in the partnership by geophysics. Some of them, perhaps influenced by a too-limited knowledge of what is happening in the search for oil, think of geophysics as a useful servant who performs necessary but somewhat menial tasks

on a commercial basis. On the other hand, not a few geologists attribute to geophysics almost magical powers in searching out hidden structure, as they suppose, with only minor assistance from geology. As several recent cooperative projects have been completed, and others are projected for the near future, it is well to examine the relative shares of the work that have been assumed, and probably will continue to be carried, respectively, by geology and geophysics.

It is a truism that science progresses from the known to the unknown. This principle is nowhere better illustrated than in the development of astronomy. If the magnificent 200-inch telescope now under construction could have been put into the hands of Galileo, with no other changes in his equipment and background, it is doubtful that he could have used it to gain any worth-while knowledge of the extra-galactic nebulae. Study of these distant objects depends on principles and techniques acquired slowly and laboriously, each a link extending a chain that can be used with confidence only because all of the links are securely joined together and lead to an anchor in observational fact. Galileo lacked such essential aids as modern spectroscopy and photography, not to mention the vast number of landmarks that have been established in the heavens by generations of astronomic research.

An optimistic view foresees a comparable development in the exploration of the Earth's interior. The picture that eventually may be obtained of the deep interior may be as novel, in comparison with what we see near the Earth's surface, as a view of the spiral nebulae would have been to Galileo; but any such picture must result from progressive extension of knowledge, starting from the zone of direct observation. If geophysics provides the equipment for probing the invisible depths, geology must indicate the most promising starting points and provide a background for interpreting the results.

Among the several geophysical techniques that are used in attacking problems of crustal structure, the gravimetric is one of the earliest in origin, although its adaptation for delimiting structural features is of comparatively recent date. The gravimetric method, so far as it involves pendulum-data, was an outgrowth of studies centering around isostasy, which, in this country, were prosecuted vigorously by Hayford and Bowie. For many years Bowie urged the importance of evaluating the effects of rock-masses near gravity-stations; and in 1923 David White pointed out a qualitative correlation between groups of gravity-anomalies and the known geologic structure [see 1 of "References" at end of paper]. White's study was of value chiefly in directing general attention to the necessity of considering the local geology in gravimetric calculations, and to the importance of locating future gravity-stations at points known for their geological significance. In the meantime, the Eötvös torsion-balance, introduced into this country from Europe, answered emphatically all doubts that the gravimetric method could be used to reveal concealed structure. Experience soon demonstrated, also, that successful operation of the torsion-balance calls for the best possible background of geologic facts and principles. By combining the resources of geology and geophysics, commercial organizations have used this instrument with notable success in solving structural problems.

Because of its extreme sensitivity, the chief function of the torsion-balance is to indicate detailed variations in structure at comparatively shallow depths. Regional studies of major structural relations employ the pendulum, preferably supplemented by the recently developed portable gravimeter. Unfortunately, the expense of owning and operating the gravimeter has so far restricted its use chiefly to commercial problems; and it is also deplorable that, up to the present, budget allocations in this country permit the maintenance of only one gravity-party for operating pendulums. However, within its narrow financial limitations in this respect the United States Coast and Geodetic Survey has cooperated generously and effectively in regional gravitational studies. For several years past, hundreds of new gravity-stations occupied by the Survey have been selected on recommendations made by geologists, with the object of aiding the investigation of major structural problems, while simultaneously contributing to the country's general geodetic program. Several fruitful projects have resulted from this policy, among them the establishing of numerous gravity-stations in the Black Hills - Bighorn - Beartooth Region, in cooperation with geological studies under the direction of W. T. Thom, Jr., W. H. Bucher, and R. T. Chamberlin. This project illustrates the ideal pooling of resources by geology and geophysics. Using all available information on the structure, stratigraphy, lithology, and geologic history of the region, geologists directed the location of stations to give the most effective summation of results. Data from groups of stations for which observational data are most complete can be used to check theoretical effects of localized variations in structure and lithology; in fact, such a check was made with some precision for a large proportion of the stations by determining specific gravities of representative rocks in all of the sedimentary formations [2]. On the other hand, in parts of the region for which geologic information is less precise than is desired, the gravimetric results serve to control inference or to indicate unsuspected changes in structure.

The same general principles have been followed in other recent gravimetric projects, among which may be mentioned, as examples, a gravity-profile running eastward across part of the Piedmont belt and the thickening wedge of Coastal Plain formations in Virginia; and a large group of stations arranged to give east-west profiles through the Hudson Valley, the New England Highlands, and the Rhode Island Basin, with emphasis on the Triassic area of Connecticut and Massachusetts. The latter project has revealed a considerable deficiency of gravity both in the Hudson Valley and in the Rhode Island Basin, with a pronounced excess in an intermediate belt extending through western Connecticut and Massachusetts. Surprisingly, there is no adequate explanation of these regional anomalies by variations in specific gravity of the near-surface bed-rock. However, there is a suggested explanation in the geologic history of the Region, for the Hudson Valley belt and the Rhode Island Basin subsided during the Paleozoic era and received thick sections of sedimentary strata, which later were severely folded. It is an attractive hypothesis that a deep-seated crustal layer of high density was so warped by these movements that its upper surface now lies much deeper in Rhode Island and eastern New York than in western Connecticut. A similar suggestion has been made for the Indian Peninsula by Glennie [3]. Possibly this hypothesis can be decisively tested by future studies which employ seismic methods.

Any discussion of gravimetric attack on major structural problems should make some mention of the work accomplished by Vening Meinesz in the East Indies, by means of a special gravity-pendulum mounted in a submarine. The belt of large negative anomalies directly outside the island-arcs is one of the most striking features known to geology. Meinesz's interpretation [4] of this belt strongly favors the Airy concept of isostatic compensation, and lends interest to tests of this concept by other methods.

Probably the gravimetric method of study has only begun to realize its possibilities. All of the projects mentioned above, and others like them, will be far more significant if the pendulum-values can be supplemented by profiles run with a gravimeter. Geologists could outline any number of projects for similar investigation, for example: Completion of gravity-profiles to settle the vexed question of the southward continuation of the Appalachian structure beneath the Coastal Plain cover; profiles across ranges and adjacent basins in the Basin and Range province, and others across some of the great thrust-faults in both the eastern and the western United States.

Seismic methods of investigating crustal structure are in many ways the most helpful now in use. Therefore, they deserve even more space than gravimetric methods; but, in the present discussion, they will be treated only briefly, since they involve a similar division of labor between geology and geophysics. Seismic prospecting, controlled by geologic information and interpretation, has achieved marked success in commercial work. The portable seismometers used in connection with blasting are fast being adapted to purely scientific investigation also. Surveys by this method have indicated astonishing thicknesses of sediments in some of the California basins, and no doubt this kind of information will increase rapidly. One of the most promising adaptations is that undertaken by Ewing to determine the structure of the Atlantic continental margin. Calibration on the geologic formations exposed on the land is an essential preliminary in this kind of project, and the entire geologic history of the region must be considered in attempts to interpret the seismic data obtained on the sea-floor. The problem has many inherent difficulties, and repeated attempts will be required for any confident conclusions. However, the reward of success will be so great that geologists and geophysicists should coordinate all possible efforts to the project.

Utilization of large quarry-blasts by means of strategically placed portable seismometers is a highly promising development recently begun in New England by Slichter. Such blasts have been used by other seismologists, but not in an extended program employing a mobile battery of receiving instruments. Several projects of this kind, operating in widely separated districts, may, within a few years, contribute more to definite knowledge of major crustal structure than has been done by all seismic studies up to the present. However, the fixed seismologic stations are as fundamental as are the pendulum gravity-stations. Aside from their major programs, many of the stations have favorable locations for studying particular features in the outer part of the Earth. A striking example is Byerly's recent work suggesting a downward protuberance of granite beneath the Sierra Nevada.

This discussion might be extended to include important work done with the magnetometer and other geophysical appliances. There is no intention to minimize their value; but time does not permit an exhaustive survey, and the purpose of this brief paper does not require it. The same principles of cooperation between geology and geophysics apply, whatever technique is used in an investigation. The few projects cited here were chosen merely to illustrate the rôle of each subject in conducting an effective attack on major structural problems. The geologist and the

geophysicist are rapidly coming to realize that many of their objectives are identical, and that each needs all the help he can get from the other. Cooperative effort is moving with an accelerating pace; and the success of recent projects dealing with crustal structure promises a rich harvest of results in the not distant future.

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MAPPING OF THE SUBMARINE VALLEYS OF THE ATLANTIC

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(Abstract)

The new basic surveys by the United States Coast and Geodetic Survey between the vicinity of Chesapeake Bay and the eastern extremity of Georges Bank have made it possible to compile accurate and detailed maps of the submarine topographic features of this region. A project (under the Penrose Bequest, of the Geological Society of America) to compile a set of special charts was undertaken by the late Dr. A. C. Veatch in 1937, in cooperation with the Coast and Geodetic Survey. These Continental-Slope Charts show not only the contours but also the vast number of soundings upon which the contours are based. These charts, and some of the important facts disclosed by them, are included in Special Paper No. 7 of the Geological Society of America. The methods employed in modern marine surveying were discussed in this "special paper" and a section of it was devoted to submarine, or "blind" contouring methods.

Editorial note: The complete report is published by the Geological Society of America as Special Paper No. 7 [101 pp., 1939]. In this volume its authors also refer to an especially instructive paper on "New methods of marine surveying," by Captain G. T. Rude, which was published as part of the symposium on the "Geophysical exploration of the ocean bottom" [Proc. Amer. Phil. Soc., v. 79, pp. 9-25, 1938].

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TOPOGRAPHY OF THE FORMER CONTINENT OF APPALACHIA (FROM GEOLOGIC EVIDENCE)

Wilbur A. Nelson

The topography of the Continent of Appalachia has varied greatly during the different geologic periods from the time of the beginning of this continent-like mass to the present.

Figure 1 summarizes in graphic fashion the sequence of earth-movements which have affected Appalachia, and illustrates how westward tilting of the continent gave place to eastward tilting after the close of the Paleozoic.

Pre-Cambrian Appalachia

During pre-Cambrian time, this continent probably extended from central Florida northward to New York City, and its western edge coincided roughly with the eastern edge of the Great Valley of the Appalachians, from Harrisburg, Pennsylvania, southward--perhaps to the western side of the present Florida peninsula. The eastern boundary of Appalachia lay out in the Atlantic, near, or possibly beyond, the edge of the present continental shelf, 50 to 100 miles east of the present shore-line, and it is known that at least the northern half of Florida was part of this continent.

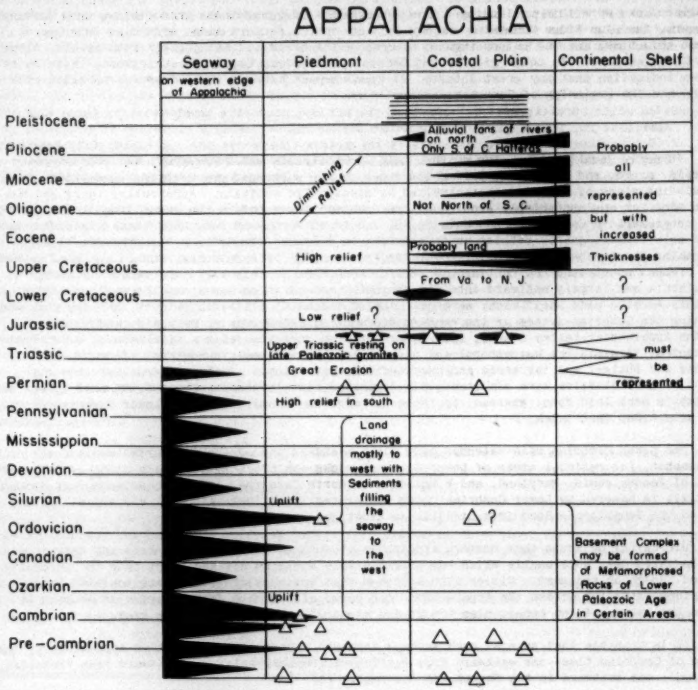

Fig. 1--Diagram illustrating uplift and westward tilting of Appalachia during Paleozoic, followed by depression and eastward tilting

(Extent and duration of principal periods and areas of sedimentation with their corresponding rock-systems shown in solid black; white indicates extent and time of erosional conditions; triangles indicate presence of igneous rocks)

The first pre-Cambrian land-surface we know, along the western edge of this continent, is the eroded surface of the Lovingston granite-gneiss, which extends from northern Virginia to southwestern Virginia. After this old metamorphosed granitic rock had been exposed by erosion, it was submerged, and coarse clastic sediments (the Rockfish conglomerate) were laid down upon it. The lower 120 feet of this formation contain large pebbles and boulders of granite--both angular and rounded--some of which are about one foot in diameter [see 1 of "References" at end of paper]. The conglomerate is best developed on Rockfish River, Nelson County, Virginia. Around Charlottesville, Virginia, the Rockfish formation grades upward into a coarse arkosic qua-tz-gneiss, the total local thickness of both formations being approximately 3,000 feet.

The 2,000 feet or more of rocks eroded from above the Lovington granite-gneiss must have been the source of the sediments which made, in part, the thick series of metamorphosed rocks which compose prominent belts of pre-Cambrian rocks in the Piedmont of Virginia.

At the close of the pre-Cambrian, extensive basic lava-flows poured out along the western portion of Appalachia from fracture-vents, burying a region of varied relief beneath several thousand feet of lava. The surface-flows covered a belt about 100 miles wide along the western edge of the old continent--at least from Maryland to southwestern Virginia--but farther south

similar flows were thin or lacking. Great batholiths of hypersthene granodiorite (now forming, in part, the Blue Ridge Mountains and the valleys on its eastern side) were also intruded at about this time, and the outpourings of lava, now preserved as the Catoctin meta-basalt, closed pre-Cambrian time. In the region around Charlottesville and Waynesboro, Virginia, there is no known indication that any great interval of time elapsed between the end of the Catoctin effusions and the beginning of Cambrian sedimentation.

Cambrian Appalachia

In early Cambrian time, the western half of Appalachia was downwarped, and coastal-plain gravels, sands, and clays were laid down on top of the submerged pre-Cambrian lava-flows, as a concluding stage of a period characterized by diastrophic activity. Apparently, there had not been time for any appreciable erosion of the Catoctin lavas before the deposition of the arkosic and conglomeratic Cambrian sandstones began, and it is worthy of note that these sandstones contain only rounded quartz-pebbles up to one inch in diameter, indicating the presence of high mountains far to the east, possibly near the eastern edge of Appalachia, and in the area between our present coast-line and continental shelf. According to this view, the ancient drainage of Appalachia was largely westward into the deepening seaway which lay along its western border. On this 40-mile wide shelf-area, were deposited the coastal-plain deposits of that day (now comprising the Cambrian system in the western Piedmont of Pennsylvania, Maryland, and Virginia). In the Appalachian Valley seaway, such Lower Cambrian deposits reach a thickness of 5,200 feet in central Virginia (at Waynesboro) and consist of coarse arkosic sandstones, ferruginous sandstones and shales, and two basic and one rhyolitic lava-flows. In Tennessee, approximately 5,500 feet of clastics were simultaneously deposited; and in Alabama about 3,300 feet of coarse sediments were laid down; whereas, to the northward, in Pennsylvania, the Lower Cambrian clastics are only 2,860 feet thick.

The Lower Cambrian seas extended many miles eastward across the downwarped western border of Appalachia, for residual areas of Lower Cambrian rocks are present in certain parts of the Piedmont of Pennsylvania, Maryland, and Virginia. In North Carolina, likewise, a large area around Linville is covered by Lower Cambrian rocks containing lava-flows--all well exposed at the big "S" on the Yonahlossee Road from Linville to Blowing Rock [2].

Ulrich [3] believes that western Appalachia at this time was not very high and that it was covered with deep soil-mantle which was progressively stripped off and swept into the deepening inland trough on the west. Ulrich also believes that branches of this seaway occupied local depressions extending across the Appalachian land-mass, affording a direct marine connection between the waters of the Appalachian trough and those of the Atlantic to the east.

It is probable that several such seaways extended across the continent of Appalachia by the close of Cambrian time--one eastward from Harrisburg, Pennsylvania; one eastward from Frederick, Maryland; one eastward in the Chesapeake Bay region [4].

Ozarkian Appalachia

Coincident with the beginning of Ozarkian time western Appalachia was uplifted sufficiently to permit the withdrawal of the seaway waters from its western submerged portion; and only limestones and dolomites were deposited along the new western shore-line of Appalachia. Apparently the streams flowing westward across Appalachia must have had little gradient and must have carried negligible amounts of clastic sediments into the western seaway. If any areas of high relief existed on the continent at this time, the drainage from these highlands must have been toward the east.

The floor of the western seaway was elevated near the close of Ozarkian time and its waters withdrawn; during an epoch in which uplift and gentle warping occurred in northern Appalachia.

Canadian Appalachia

Canadian deposition was inaugurated by renewed subsidence in the western trough [5] and during ensuing Canadian time conditions on Appalachia were very similar to those just postulated for the Ozarkian; but shallow seas spread over much of Appalachia, and limestones and dolomites were laid down in depressions that penetrated far into the continent, especially in Pennsylvania and Maryland [6]. Limestones of Lower Paleozoic [7] age also occur east of the Blue Ridge in Virginia and even east of Southwest Mountain; and, though these have been assigned to the Ordovician on the basis of fragmentary fossil evidence, it is the writer's belief that their general structural relationships indicate an age comparable with that of the Conestoga limestone of Pennsylvania [8], which is probably the equivalent of the Upper Canadian Cotter dolomite of Missouri.

Ordovician Appalachia

During Ordovician time, Appalachia lay near sea-level; arms of the sea invaded the continental area; and in them were deposited fine-grained sediments, such as those of the Arvonia slate, and of the Occoquan slate-belt, which is on the "Fall Line" south of Washington, D. C. At Arvonia, the slates lie unconformably on pre-Cambrian rocks, as shown by well-exposed contacts one-half mile south of Carysbrook, Virginia; and Ulrich considers the Arvonia deposits to be remnants of sediments deposited in a strait connecting the Atlantic Ocean with the epicontinental sea lying west of Appalachia. The occurrence within these slates of an ash-bed, several feet thick, indicates that some volcanic activity was taking place at this time in the central part of Virginia [9] and probably elsewhere in the Piedmont and eastern United States [10,11].

Schistose rhyolite flows also occur in the Arvonia area [12], and unmetamorphosed rhyolites are interbedded with the Ordovician slates at Occoquan. Hence, special interest attaches to the report by Ross [13], which shows that the deep well at Fortress Monroe, Virginia, penetrated a metamorphosed ash-fall underneath the cover of present Coastal Plain deposits. As stated by Ross:

"These rock fragments from Fortress Monroe well all represent a devitrified volcanic ash of rhyolitic character. Notwithstanding the devitrification, the ash structure is well retained in at least two of the five sections that I had made. The only unaltered phenocrysts (quartz) are very sparse, and show marked rounding by resorption. Others, also rare, represent partly altered feldspar.

"The fragments in the best specimen are rather well sorted, and reach about 0.3 millimeter in maximum dimension. Hence, they seem to represent material that fell far enough from the volcanic center for fair sorting to occur.

"The very finely crystalline material resulting from devitrification is, in part, secondary quartz."

This rhyolitic rock forms the basement of the Coastal Plain at Fortress Monroe. Lonsdale has described the Quantico rhyolites [14] (which he considered to be post-Ordovician in age, as they are totally unmetamorphosed).

At the close of the Ordovician, a general uplift of western Appalachia took place, and the northeastern part of the land-mass suffered severe deformation at this time, for an angular unconformity may be seen locally between the Ordovician beds and the overlying sediments [15].

During the Ordovician, 300 feet of clastic sediments were laid down in Alabama, compared with 4,500 feet in Tennessee, 3,000 feet in Virginia, and 1,000 feet in Pennsylvania. Both the minor amounts of sediment and its shaly character indicate a low topographic relief for the land-mass.

Silurian Appalachia

During Silurian time, the relatively swift streams which flowed westward across the re-elevated surface of western Appalachia carried large amounts of sand, as well as clayey material, into the Appalachian seaway, causing the deposition of massive sandstones, some very pure, some ferruginous; together with thick sandy shales. In Alabama, 270 feet of clastics were deposited. In Tennessee, 1,500 feet of clastics were laid down; in Virginia, 1,000 feet of sandstones and shales were deposited; and in Pennsylvania, 1,770 feet of conglomerates, coarse sandstones, and shales accumulated.

It is interesting to note that the massive Silurian sandstones now found in the former Appalachian seaway, from Pennsylvania to Tennessee, are devoid of mica. Apparently, no micaceous metamorphic or igneous rocks were contributing sediment to the westward-flowing drainage during this period.

In Middle and Upper Silurian time, there was at least one opening in Appalachia, probably along the New Jersey "gateway," permitting Atlantic waters to enter the Appalachian trough which, at this time, was deepened from New York southward to Tennessee.

Devonian Appalachia

Our ideas of Devonian conditions in western Appalachia are based upon inferences as to the meanings of varying thickness of sediments deposited in the different parts of the western seaway. In Alabama, approximately 800 feet of Devonian clastics were laid down, and only 50 feet of limestone. In Tennessee, only Middle Devonian sediments are found, and these consist almost entirely of shales and sandstones, having a total thickness of slightly less than 200 feet; whereas 2,400 feet of sediments were deposited in northern Virginia, of which 2,100 feet were

clastics and 300 feet were limestone. Farther west in Virginia 7,500 feet of clastics were deposited; and 12,200 feet of sediments accumulated in Pennsylvania, of which 11,900 feet were clastics, mostly shale. Ulrich [16] considers that the great thickness of Devonian clastics deposited is due to an inland migration of the belts of folding and not to any great crustal movement.

It, therefore, appears that southern Appalachia was not a region of high relief or of rugged topography during Devonian time, but that the surface of the region was repeatedly elevated during this period, but none of these movements were of any magnitude. The strongest uplift occurred in the northern part of Devonian Appalachia.

During most of the Devonian, Appalachia was separated from the land-mass of Taconia by what is known as the "New Jersey Strait," but it probably continued southward as an unbroken land-mass to the latitude of Florida. Devonian seas having Atlantic connections were those of the Helderberg, Oriskany, Marcellus, Genessee, Portage, and Chemung formations [17].

Mississippian Appalachia

During Mississippian time, Appalachia continued to supply finer or coarser clastics to the seaway on its western border, though during middle Mississippian time Appalachia was reduced nearly to base-level, and practically all of the sediments of this age are, consequently, limestones and highly calcareous shales. From the standpoint of thickness of sediments deposited in the western seaway, the greatest elevation of Appalachia during this period should have been adjacent to the local depressions (within the general Appalachian trough) which were developing in Alabama, in southwest Virginia, and in central Pennsylvania. In consequence of the varying depth of the Appalachian trough, the Mississippian clastics are 3,900 feet thick in Alabama, 750 feet in Tennessee, 4,775 feet in southwestern Virginia [18] and 4,300 feet in Pennsylvania.

During most of this time, the New Jersey Strait to the Atlantic probably was closed, and Appalachia and Taconia probably were joined.

Pennsylvania Appalachia

During Pennsylvania time, the recurring uplifts to which Appalachia had been previously subjected culminated in great upward movements--in early Pennsylvanian (Pottsville) time in the southwestern part of Appalachia and somewhat later in the Maryland and Pennsylvania parts of Appalachia. In consequence of these movements, the surface of Appalachia evidently became mountainous and shed great quantities of gravels and coarse sands (as well as clays) into the coal-basins which were forming within the old seaway--at least 9,000 feet of relatively coarse clastics making up the Pottsville coal-measures of Alabama, and approximately 5,000 feet of similar material occurring in Tennessee and southwest Virginia.

Practically all of the sandstones laid down during the Pennsylvanian were highly micaceous, showing that the streams which deposited them were flowing across a land-surface composed either of pre-Cambrian crystallines or of older Paleozoic terranes which had already been metamorphosed by burial and deformation.

Permian and Triassic Appalachia

About the close of Pennsylvanian time, and within the borders of Appalachia, great batholiths of granite were intruded--some of which crop out just to the east of the foot of the Blue Ridge--around Mt. Airy, North Carolina, and elsewhere in the Piedmont of North Carolina, South Carolina, and Georgia. The presence of similar granites beneath the present Coastal Plain deposits is revealed by deep wells, and by outcrops just east of the Fall Line from Richmond southward.

We can date very closely one of the periods of profound erosion in Appalachia, because a batholith occurring near Richmond, known as the Petersburg granite, which was intruded after Appalachian folding had ceased, is the basement on which Upper Triassic sediments were deposited in the Richmond coal-basin [19].

In this region during Permian and Early to Middle Triassic time, at least 2,000 feet of cover must have been removed from the granite, after Appalachian folding had ceased and before Upper Triassic sediments were laid down on its eroded surface. Yet, in spite of such deep erosion in Appalachia, only minor sedimentary deposits of Permian age occur in the former western seaway, and no sediments of Lower or Middle Triassic age exist. Hence, it is necessary to

postulate that throughout Upper Permian and Lower Triassic time, the streams on the land-surface of Appalachia had ceased to flow westward, and that they were, instead, depositing their transported debris on part of the then Atlantic Ocean floor--probably that which is now occupied by the Continental Shelf of today. It is considered that underlying the Continental Shelf there must be sediments of Upper Permian and Lower Triassic age.

Coincident with, or in consequence of, the change in tilt of the land-surface from westward to eastward, faulting broke the old land-mass into linear blocks; tilting and settling of these blocks occurred; and Upper Triassic sediments were deposited in the troughs thus formed. The Triassic rocks were then further tilted and were intruded by dikes and sills of diabase.

In addition to the Triassic basins which are exposed in the Piedmont from New York to North Carolina, similar Triassic areas lie buried beneath the present Atlantic Coastal Plain in at least three localities, as revealed by deep wells. Thus, at Florence, South Carolina, Triassic sediments were encountered in a well at a depth of 1,300 feet. At Summerville, in Dorchester County, South Carolina, Triassic rocks were penetrated at 1,580 feet, and at 2,570 feet the well was stopped in Triassic diabase. And at Bowling Green, Virginia, Triassic beds were penetrated from a depth of 533 feet to the bottom of the well at 1,720 feet. Other concealed Triassic basins will undoubtedly be found as exploration progresses, and it is probable that the included Triassic sills and dikes will make distinct ridges upon the buried land-surface of Appalachia [20]. It is, moreover, possible that there are important causal connections between the faults which bound the Summerville Triassic basin, and the earth-movement responsible for the nearby Charleston earthquake of 1886, the epicenter of which was at Summerville.

Jurassic Appalachia

The northern part of Appalachia may have been characterized by a varied topographic relief during Jurassic time, but to the south, where the Triassic faulting was less, a low relief probably prevailed during this period. Drainage of the land-surface continued to be eastward, and the absence of Jurassic sediments from the emergent part of the Atlantic Coastal Plain indicates that the shore-line at that time lay far out under the present Atlantic Ocean.

Lower Cretaceous Appalachia

During Lower Cretaceous time, the progressive eastward tilting and subsidence of the eastern part of Appalachia led to the intiation of Coastal Plain sedimentation such as had characterized the Atlantic seaboard-region ever since. The eastern part of Appalachia may have been a land of low relief extending out toward the Continental Shelf or a region covered in most part by continental deposits. This old pre-Cretaceous land-surface of Appalachia is still preserved as the basement on which the Coastal Plain deposits were laid down. Such is true in Mathews County, Virginia, on Chesapeake Bay, where a well drilled in 1929 encountered the Petersburg granite of Late Paleozoic age forming the basement of the Coastal Plain deposits at a depth of 2,307 feet. This granite has a specific gravity of 2.6. The gravity-anomaly at this point is 23. However, east of the Lower Cretaceous strand-line, marine sands and clays were deposited, and west of this strand-line flood-plain and fresh-water deposits were laid down--and, as subsidence gained on sedimentation, the zones of marine and fresh-water deposition were sympathetically shifted. The old pre-Cretaceous land-surface of Appalachia is thus still preserved east of the Fall Line, and is the surface upon which the Cretaceous Coastal Plain deposits came to rest.

Detailed information as to the character of the buried surface in one area is provided by a subsurface map of the Baltimore City area, compiled in 1935 under the direction of Dr. E. B. Mathews, of the Maryland Geological Survey [21] (see Fig. 2). The pre-Cretaceous drainage does not coincide with the present-day drainage except in that part of Baltimore which lies to the west of the Fall Line.

An equally well-developed drainage-system and topographic pattern is undoubtedly present beneath the whole of the Atlantic Coastal Plain, but inasmuch as there are fewer than 30 deep wells in the whole Coastal Plain region, from New Jersey to Florida, the geologic evidence as to configuration of the pre-Cretaceous floor (that is, the form of the buried land-surface of Appalachia) is so scanty that one can only depict the general form of this surface by 1,000-foot contours (Fig. 3), as compared with the 20-foot contours used for the Baltimore area (Fig. 2). The contours of Figure 3 disclose several interesting features. Toward the north, in New Jersey, the buried surface of Appalachia slopes seaward more rapidly (80 feet per mile) than in any other area within the present Atlantic Coastal Plain. In the Chesapeake Bay region of Virginia, the eastward slope is about 43 feet per mile; and along the North Carolina-South Carolina State-line, it decreases to 12 feet per mile, for here we have a distinct structural uplift or warping

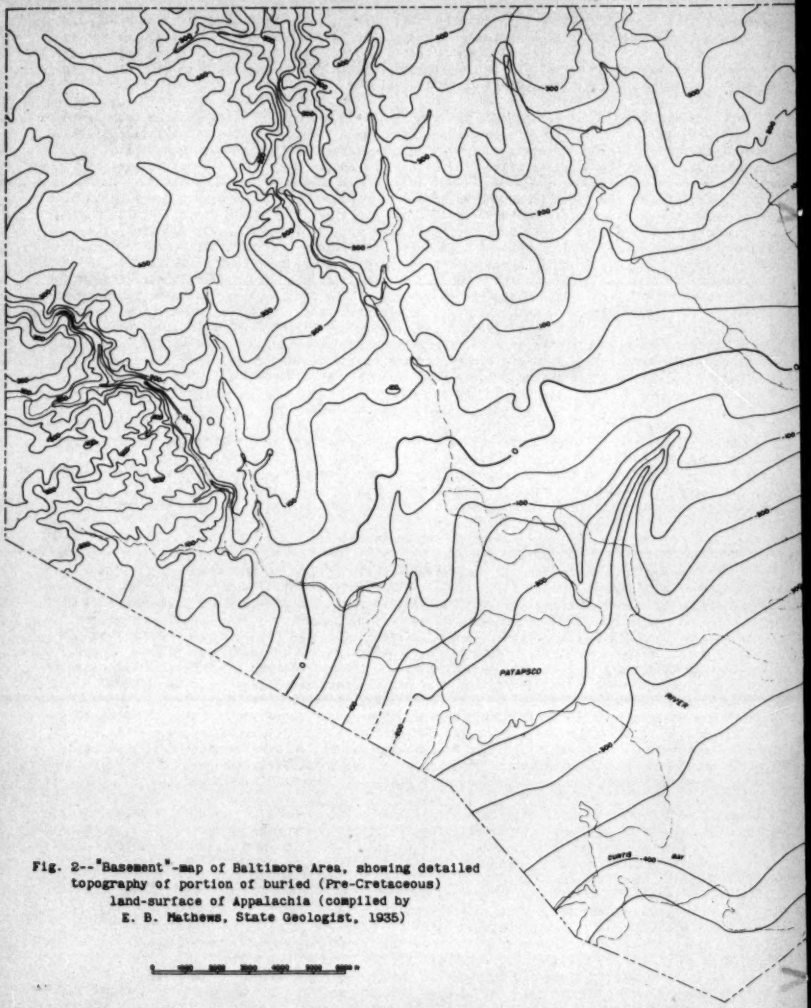

Fig. 2--"Basement"-map of Baltimore Area, showing detailed topography of portion of buried (Pre-Cretaceous) land-surface of Appalachia (compiled by E. B. Mathews, State Geologist, 1935)

of the pre-Cretaceous land-surface. Here the basement-complex on which the Cretaceous rocks rest is encountered at a depth of only 1,580 feet at Fort Caswell, situated at the mouth of Cape Fear River [22], whereas, at an equal distance from the Fall Line in Georgia, the basement-complex is reached at a depth approximating 3,500 feet. In Georgia, the slope of the old pre-Cretaceous land-surface is at the rate of 32 feet per mile, to the southeast. A few wells

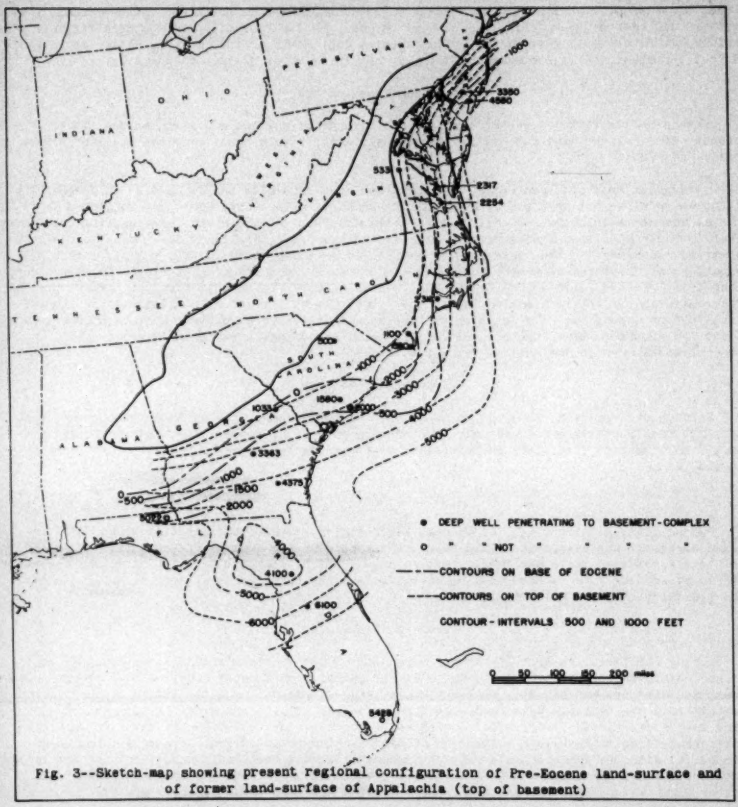

Fig. 3--Sketch-map showing present regional configuration of Pre-Eocene land-surface and of former land-surface of Appalachia (top of basement)

drilled in Florida, two of which reached the basement-complex, give information in regard to the platform on which Florida was built. From this information, and from the structure-map of Florida, published by the Florida Survey [23], the buried topography of this part of Appalachia has been reconstructed to show a low dome-like area underlying the north-central part of the State.

Upper Cretaceous Appalachia

At the beginning of and during Upper Cretaceous time, the whole of Appalachia underwent further eastward tilting and downwarping, in consequence of which the shore-line retreated westward to and in places beyond the present Fall Line--the Upper Cretaceous sea advancing slowly across this subsiding land-surface of low relief. Sedimentation kept pace with depression throughout the present Coastal Plain until the close of Upper Cretaceous time, when the submerged area was elevated relative to sea-level, and the shore-line retreated far to the east and south, perhaps close to the edge of the Continental Shelf [24]. Consequently, throughout the entire Atlantic and Gulf Coast region the Upper Cretaceous is separated from the overlying Eocene by an unconformity of regional extent. One thousand-foot contour-lines have been drawn throughout the Atlantic Coastal Plain region on the base of the Eocene (Fig. 3), and they show that this surface

slopes eastward more gently than does the old sub-Cretaceous land-surface. In New Jersey, the eastward dip of the Upper Cretaceous surface is about 50 feet per mile; in southern Virginia at Norfolk, it is about 13 feet per mile; in Carolina just north of the Carolina Ridge, it is about 15 feet per mile; and in southwestern Georgia the dip is about 30 feet to the mile.

Eocene Appalachia

Eocene sedimentation began with a westward advance of the sea across an eroded, Upper Cretaceous, land-surface, and resulted in the deposition of a thin basal conglomerate overlain by marine beds [25].

Throughout most of Eocene time, sedimentation kept pace with the depression or downwarping of the eastern part of Appalachia, but, in late Eocene, eastern Appalachia was subjected to crustal movements which raised the region between Cape Fear River, North Carolina, and the Santee River in South Carolina, producing what is known as the Great Carolina Ridge [26]. No Claiborne formations representing the upper part of the Eocene were deposited in this region, although formations of Claiborne time were deposited to the north and south of this ridge. Northwestward along this line the Piedmont and Great Smoky Mountains were elevated to form the highest part of Appalachia, and in the Appalachian Valley the Wytheville barrier or axis which existed intermittently during Ordovician to Mississippian time appears to be on an extension of this Eocene axis. At the end of Eocene time, the present Coastal Plain region again emerged above sea-level, and the continental margin was shifted far eastward.

Oligocene Appalachia

Throughout Oligocene time, the northern part of the present Coastal Plain region was emergent, but from South Carolina southward submergence late in Oligocene time again permitted the deposition of marine formations in southeastern Appalachia from South Carolina to Florida and Alabama.

Miocene Appalachia

During Lower Miocene time, the Coastal Plain region north of the Carolina Ridge still remained emergent, whereas to the south only a small part of the Coastal Plain in South Carolina and Georgia remained above sea-level. But in late Upper Miocene the Carolina Ridge had been lowered by erosion, and renewed depression led to another submergence of the Coastal Plain region from Maryland to Florida [27].

Pliocene Appalachia

During Pliocene time most of the northern half of the Continental Shelf was probably land, and the mainland back of it probably had a higher relief than it does today. South of Cape Hatteras, the Piedmont was probably of lower relief than at present, and the margin of our present Coastal Plain was slightly submerged. To the north, the alluvial fans of the Susquehanna and other rivers were probably deposited during the Pliocene. The deposition of these marine and continental deposits in Pliocene time was stopped by widespread crustal movements which ended this period with the coastal-plain part of Appalachia almost completely submerged. In New Jersey little of the Coastal Plain remained above sea-level. In South Carolina three-fourths of the Coastal Plain was covered by the ocean, while Florida was downwarped to the west [27].

Pleistocene Appalachia

During Pleistocene time the history of land-movements on the coastal-plain part of Appalachia is shown by the terrace-formations which have been deposited from New Jersey to Florida. In each case it is felt that the sea withdrew from the land and then rose. There are five such terrace-levels, which have been recognized by different workers in this coastal plain region [28].

Summary

The land-surface of the continent of Appalachia has varied greatly in its extent, its boundaries, and its topographies throughout geologic time. These changes are best summarized by Figure 1, which shows that Appalachia was a continent separated from the mainland mass of the North American Continent throughout most of Paleozoic time; that during Cambrian time Appalachia had a western submerged coastal plain upon which were deposited sediments of that age; that later on shallow seas, in which limestone was deposited, covered parts of this low-relief continent;

that during Ordovician time straits probably had separated Appalachia into a series of island-like masses; and that there was igneous activity in this region in pre-Cambrian, Cambrian, Ordovician, and Triassic times.

During Paleozoic time westward flowing streams deposited the weathered rocks and soil of Appalachia in its western seaway, until over 20,000 feet of Paleozoic sediments eventually filled this trough, and with the culmination of the great upward movements and westward thrusting of Appalachia against this old filled-in seaway (the Appalachian Mountain revolution) completed the bonding of Appalachia to the land-area of North America to the west.

At the close of this mountain-building period Appalachia was subjected to great erosion, coincident with the change in tilt of land-surface from westward to eastward. Following this time interval and during Triassic time tensional faulting broke the old land-mass into linear blocks and local subsidence began.

During the Cretaceous, progressive eastward tilting and subsidence of the eastern part of Appalachia led to coastal-plain sedimentation, such as has characterized the Atlantic seaboard-region ever since. During much of this time sedimentation has kept pace with depression.

Today a study, by geophysical means, of the buried topography of the coastal-plain region out to and beyond the Continental Shelf is of especial importance to determine the thickness and character of the sediments lying above the basement-complex. The scale and character of the local topographic relief on the sub-Cretaceous erosion-surface is shown in Figure 2; and the degree of regional tilting and downwarping which this surface has undergone is summarized in Figure 3.

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PRESENT POSITION OF THE FORMER TOPOGRAPHIC SURFACE OF APPALACHIA (FROM SEISMIC EVIDENCE)

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Introduction

The foregoing paper by Professor Nelson [see 1 of "References" at end of paper] has traced the evolution of the sub-Cretaceous land-surface of Appalachia and has cited the geologic evidence indicative of both the rate of (seaward) slope, and the nature of the topographic relief characterizing this former continental surface. In the present paper, I will present a geophysical continuation of Dr. Nelson's geologic story and will describe how the seismic method of geophysical exploration has been, and may be, used in the further mapping of the buried Appalachian land-surface--both within the area of the present Atlantic Coastal Plain, and within the western part of the Atlantic. Seismic explorations within these areas have not, it is true, as yet passed beyond the reconnaissance-stage; but, even so, the results already obtained have led to positive conclusions and have justified the formulation of much more extensive exploratory projects. The latter are even now getting under way, and presage both extensive and intensive seismic exploration of coastal areas from New England to Florida.

Historic background of Atlantic Coastal Plain seismic studies

Thanks to the work of exploratory geophysicists engaged in oil-field work, especially within the Gulf Coast region of the United States, it became evident some years ago that the refraction-method of seismic prospecting could be used to solve some of the major geophysical-geological problems connected with continental borders, and also that this method could be used to explore subsurface conditions in any section of the Coastal Plain.

The feasibility of using the seismic method for the study of submarine geology was likewise pointed out by De Golyer [2] in a paper forming part of a symposium on the "Application of geophysics to ocean-basins and margins," which was presented before the annual meeting of the American Geophysical Union in April, 1932. Furthermore, by 1935 it had become apparent that the Atlantic Coastal Plain-Continental Shelf region of the Eastern United States afforded an unusually favorable "laboratory-area [3] for studying one continental border--to determine whether the North American continent has a sharply-marked structural or lithologic eastern border, or whether both of the apparent continental borders (the present strand-line, and the outer margin of the Continental Shelf) are merely ephemeral topographic features, dependent for their present location upon the momentary position of one main geologic variable--namely, sea-level.

The first actual seismic experimentation undertaken in the Atlantic Coastal Plain, in the attempt to determine the depth and slope of the buried Appalachian topographic surface, was carried out in 1935 [4], beginning with various tests near the deep bore-hole at Jackson's Mills, New Jersey; and it was continued by marine (reflection) seismic tests conducted from the ship Oceanographer of the United States Coast and Geodetic Survey. Land-calibration tests near Fortress Monroe and Petersburg, Virginia, were next undertaken, and actual application of the refraction method to subsurface surveying in marine areas was begun in the autumn of 1935, by running two marine traverses--one southward from Woods Hole, Massachusetts, and the second eastward from Cape Henry, Virginia--this work being made possible through the cooperative use of the ship Atlantis of the Woods Hole Oceanographic Institute.

The foregoing experiments, plus others subsequently conducted in the Coastal Plain of New Jersey [5], and current experimentation in the adaptation of seismic techniques and appliances to deep-water surveying will make it possible to trace the eroded surface of the (pre-Cretaceous) "basement"-rocks eastward and seaward from their outcrop along the Fall Line--until it has been demonstrated either that the part of the Earth's crust underlying the North American continent is essentially continuous with that underlying the North Atlantic basin, or that there is a definite structural and lithologic "break," or margin, near the outer edge of the continental shelf, which separates "continent" from "ocean-basin."

Use of the seismic refraction-method in tracing the surface of the "basement-complex"

It is possible to use the seismic refraction-method to explore the buried land-surface of Appalachia (hereafter to be referred to as "the surface of the basement-complex" for brevity's sake), because of the great difference in speed with which seismic waves travel through the "basement"-rocks, and through the Coastal Plain sedimentary strata which overlie this "basement." By making use of these travel-time differences, and by employing the familiar principles of wave-refraction, it has been possible both to obtain accurate determinations of the subsurface position of the basement-surface at various localities, and to obtain indications that the local basement topographic relief in parts of New Jersey is closely comparable to that found in the Baltimore area, as shown by Figure 2 of Professor Nelson's paper. Such seismic information as has been acquired regarding the sea-level position and relative topographic relief and slope of the old Appalachian land-surface, is also excellently expressed by the "basement-surface" contours shown in Dr. Nelson's Figure 3.

As is known to those familiar with the seismic refraction-method, the quantity which is measured directly in such work is the time required for a vibration or seismic wave to travel through the ground from one point to another, the two points being at or near the surface. The vibrations are generated by means of an explosion, and the point at which they originate is usually called the shot-point. Their arrival at the recording-point is detected by a microphone, usually called a geophone, which is especially designed for reception of vibrations travelling in the Earth. The seismic waves detected by the geophone are amplified and are then recorded photographically on a strip of sensitized paper, which moves at known speed in an oscillograph.

Also recorded on this strip of paper is a signal--transmitted from the shot-point over a temporary telephone-line, or by radio--which indicates the instant at which the explosion occurred. The travel-time of the seismic wave is thus obtained from the photographic record, as the interval between reception of the radio or telephone-signal, and the time of arrival of the vibrations which have travelled through the Earth. Figure 1 is a copy of a seismogram obtained from the explosion of eight pounds of dynamite at one of the stations in the Coastal Plain. On this occasion, six geophones were placed at distances of 7,040 to 9,040 feet from the shot-point. There is one trace in Figure 1 to indicate the ground-motion at each geophone. Time is measured, from the point marked zero at the left-hand end of the record, by the aid of the transverse lines which are placed on the record at intervals of approximately 0.005 of a second. The scale of travel-time established by these lines is written near the bottom of the record.

It should be noted that three successive waves are clearly recorded for each geophone-distance, these being marked with the letters A, B, and C. The velocity with which each wave is traveling past the geophones is readily computed from the time-interval between arrival of the wave at the first and last geophones. The velocities thus determined are 17,500, 6,800, and 5,100 feet per second for A, B, and C, respectively. (Numbers written on the record other than those mentioned above are not relevant to the present discussion.)

By use of additional records taken with the geophones nearer to the shot-point, it may readily be demonstrated that the waves marked C have travelled directly from the shot-point to the recording-point through the uppermost layers of the earth, at a speed of 5,100 feet per second. Those marked B have gone down through the upper layer (Layer I) at the shot-point, have travelled across to the recording-point in a second layer (Layer II) in which their velocity is 6,800 feet per second, and have then returned to the surface through the Layer I. These waves have travelled a greater distance than the direct ones, but have arrived earlier because the distance from shot- to recording-point was, in this instance, sufficiently great (in comparison with the thickness of the Layer I) to allow the relative velocity-increase in Layer II to more than compensate for the additional distance travelled by the wave which traversed Layer II.

In like manner, the waves marked A have gone down to the basement-rocks (of Layer III) at the shot-point, have travelled horizontally in them with a velocity of 17,500 feet per second,

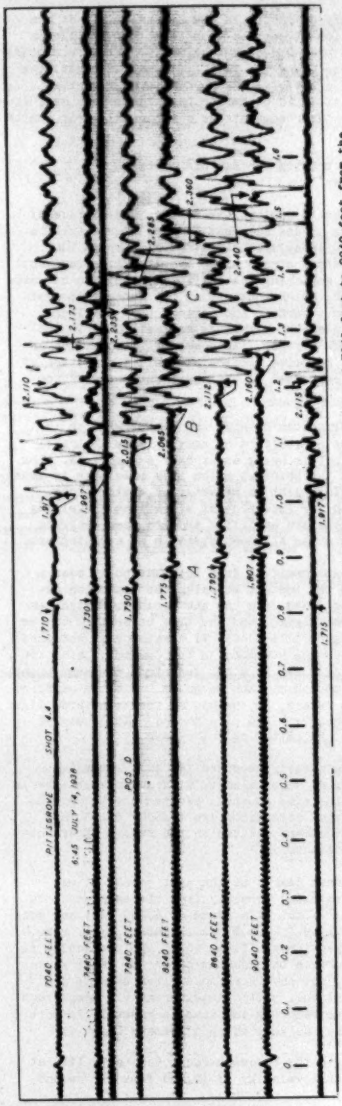

Fig. 1--Seismograms obtained in Atlantic Coastal Plain with six geophones spaced 7040 feet to 9040 feet from the shot-point; waves marked A have traveled through basement-rocks and those marked B and C through overlying sediments (reproduction is 0.8 size of original record)

and have then returned to the surface at the recording-points. By virtue of the high velocity encountered in the basement-rocks, this wave arrives ahead of the others, when the distance between the shot- and recording-points is sufficiently great.

In order thus to determine the depth to basement-rocks by seismic refraction-measurements, it is necessary to carry the measurement of travel-time to distances great enough to permit the waves marked A in Figure 1 (they are usually called the refracted waves) to arrive at the geophones ahead of the others. Being the least intense of the several waves, they are usually obscured if the others arrive ahead of them. This usually involves the measurement of travel-times over horizontal distances of from three to four times the depth to be measured--the exact factor depending upon the exact velocity-contrast between the upper and lower media.

It is simplest to consider the depth to basement so obtained as an average depth over the entire length of the line of measurement, but more detailed observation can be made to yield information on depth-variations caused by local basement-topography in cases where there is need for more precise knowledge concerning concealed topographic irregularities.

Seismic measurements already made or projected

On land-areas--Figure 2 shows the locations of the seismic depth-measurements which have been made up to the present time. Lines of land-stations have been run across the Coastal Plain at Cape Henry, Virginia [6]; at Cape May, New Jersey [7]; and at Barnegat Bay, New Jersey [8]; and the depth to the basement-rocks has been measured at intervals of from five to eight miles along each of these lines. It is also hoped that similar measurement can soon be made on Long Island, in Maryland, and in Delaware, so as to draw rather detailed contours on the basement-surface over the whole region extending from Cape Henry to the eastern end of Long Island.

The measurements already made have verified and extended the knowledge available from the few deep wells which have reached the basement in the area under consideration. They show a rather gradual and uniform seaward dip of the buried basement-surface--from its outcrop at the Fall Line, to the present shore. The depths to the basement-rocks at the coast-line are shown to be in the neighborhood of a mile.

Shallow-water measurements--The continental shelf, which includes the area between

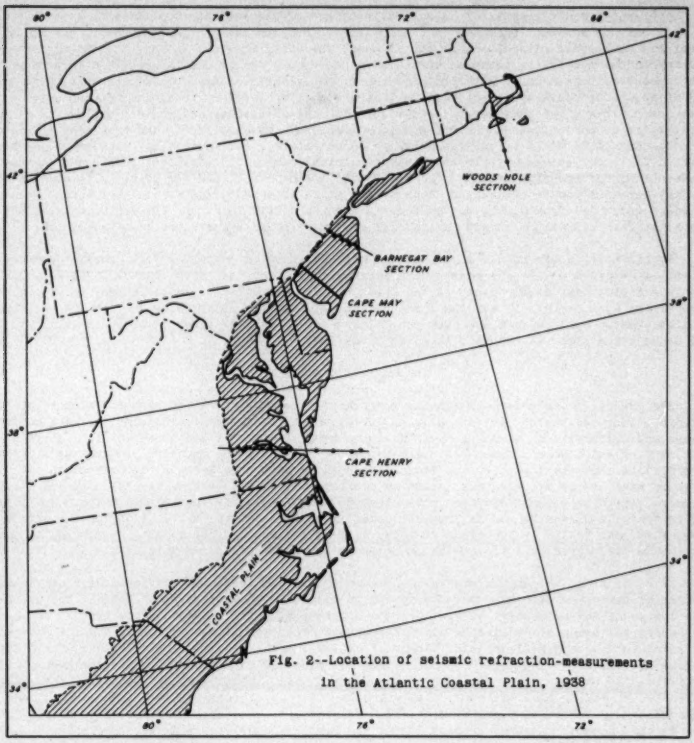

Fig. 2--Location of seismic refraction-measurements in the Atlantic Coastal Plain, 1938

the coast-line and the 100-fathom line, is about 80 miles wide off the Virginia Capes, and is characterized by a relatively flat surface, terminated seaward by a relatively more rapid downward slope to the main floor of the ocean. A line of refraction-measurements made across the continental shelf [9] revealed an increase in depth to the top of the basement-complex to about two miles near the eastern shelf-margin. Urgent need exists for comparable lines of measurement across other parts of the shelf, and plans have been drawn up for a program of such work in the near future.

The procedure for seismic refraction-work in shallow water does not differ greatly from that used on land. Two boats are used. The recording-equipment is carried on board one of the boats, a geophone being dropped to the sea-bottom by means of the electrical cable which connects it to the recording-apparatus. The equipment for firing the bombs and for transmitting a radio signal at the instant of explosion is installed in the second boat. The bombs are lowered to the bottom before being exploded; and the travel-time of the water-wave from the shot-point to the receiving-station is used to determine the direct distance between bomb and geophone.

Bullard [10], working off the coast of England with apparatus and technique similar to our own, has obtained results analogous with those secured by us along our line of stations off Cape Henry [11].

Deep-water measurements--It is naturally of great interest and importance to determine whether or not the basement-surface, as traced seaward beneath the continental shelf, continues out under the deep ocean without change at, or near, the shelf-margin. The development of instruments and techniques for making seismic refraction-measurements on the ocean-floor, and in deep water, has consequently been under way for three years. Inevitably, marked modifications both of method and of appliances have had to be made in order to meet exploratory conditions encountered in the open ocean. New bombs have had to be devised, for the problem of setting off explosives beneath three miles or more of water had not previously arisen. New amplifying and recording apparatus also has had to be built--apparatus which would be entirely self-operating--because of the great difficulty in obtaining multiple-conductor electrical cables of sufficient length and strength. A new method for lowering needed apparatus to the ocean-bottom, and for bringing it back to the surface has also had to be devised, because two years of work during which steel cables were used to lower geophones from a ship proved that it was too difficult to prevent disturbance to the geophones from vibrations caused by the roll of the ship and transmitted down the cables.

Fortunately, a new set of apparatus has been built which meets the requirements just stated, as well as various additional ones. This apparatus will soon be tested further, but it is confidently expected that measurements of the depth to the basement-rocks will thereby be obtainable, even in the open ocean. If so, the means will be at hand for determining whether the old Appalachian erosion-surface does, or does not, extend out beyond the edge of the Continental Shelf, and beneath the floor of the main Atlantic Ocean Basin.

Summary and conclusion

The general procedures on which the program of seismic exploration has been planned are divisible into two parts: An initial one, during which the geophysical exploratory-method is tested and calibrated in areas of known geologic condition; and a second exploratory phase of work, during which observations are carried step-by-step into the unknown. In keeping with rules of procedure, the locations for the measurements which have been made on land have been selected so as to make use of existing deep wells as check-points on the seismic results obtained. Furthermore, especial thought has been given toward the invention of instruments which can be operated in the Gulf Stream, so as to prevent breaks in profile-continuity, just beyond the edge of the Continental Shelf, in consequence of the differences in physical condition between the waters within the Gulf Stream and those within the ocean alongside and below this stream.

In conclusion, the writer wishes to point out that his attention was first directed to the problem of making seismic measurements at sea in 1935 through Professor R. M. Field and Dr. William Bowie, acting as members of the American Geophysical Union's Special Committee on Geophysical and Geological Study of Oceanic Basins. Throughout, this Committee has maintained its interest and rendered valuable advisory aid. Grants from the Penrose Bequest of the Geological Society of America have financed most of the project thus far executed; and the Woods Hole Oceanographic Institute, the Bermuda Biological Station, and the United States Coast and Geodetic Survey have cooperated by making their ships available for experiments at various times. The John Simon Guggenheim Memorial Foundation (by award of a fellowship) has enabled the writer to devote full time to this general research-project during the years 1938-39, and 1939-40. Professor B. L. Miller, of Lehigh University, has been geological adviser during the early phases of this work; and A. P. Crary, A. C. Vine, G. P. Woollard, N. H. Heck, and others have taken very active and helpful parts in the project at one stage or another.

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[5] Maurice Ewing, G. P. Woollard, and A. C. Vine, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part III, Bull. Geol. Soc. Amer., v. 50, pp. 257-296, 1939.
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[9] Maurice Ewing, A. P. Crary, and H. M. Rutherford, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part I, Bull. Geol. Soc. Amer., v. 48, pp. 753-802, 1937.
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GRAVITATIONAL DETERMINATION OF DEEP-SEATED CRUSTAL STRUCTURE OF CONTINENTAL BORDERS (OBSERVATIONS AND METHODS)

C. H. Swick

It is evident that gravity-data are of considerable value in investigations of deep-seated crustal structure; and many geologists are making increasing use of gravity-anomalies, both in studying fundamental processes involved in deformations of the Earth's crust, and in learning the location and extent of large masses of rock of abnormal density, concealed in the Earth.

Because gravity-data have thus been found useful in extending our knowledge of the crust to far greater depths than can be reached by most other methods of geological investigation, many geologists have become especially interested in gravity-surveys and have made intensive studies of the data thus obtained to supplement their observations of surface-structures.

Of the many organizations making gravity-determinations in this country, only the United States Coast and Geodetic Survey makes its results available for general use. The others are

[A] As set up for observations showing device (tall box) used to record oscillations of pendulum on chronograph; pendulum receiver is in white box which is supported in hollow pier of Plaster of Paris

[B] Lower part contains pendulum and upper part records oscillations on chronograph
[C] Heavy metal box to support receiver for pendulum

Fig. 1--Brown gravity-apparatus

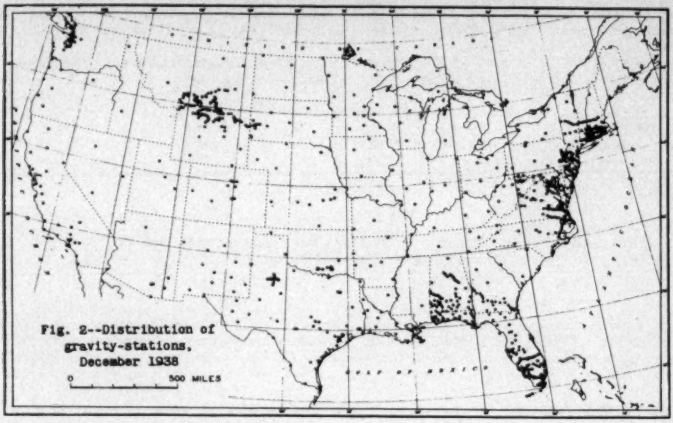


Fig. 2--Distribution of gravity-stations, December 1938

engaged chiefly in economic explorations for oil or other minerals and for this reason have only rarely released their data for scientific investigations along other lines.

The United States Coast and Geodetic Survey uses a pendulum-apparatus and therefore cannot compete with the oil-companies in speed of operation, as the latter use gravimeters. The reason we do not use the faster gravimeters is that our stations must be distributed over the whole extent of the country, and the determinations must be based upon the recognized world gravity-datum, instead of upon a strictly local system. The United States Coast and Geodetic Survey uses the Brown pendulum-apparatus and on all recent surveys has employed two sets of the apparatus to insure the integrity of the results (see Fig. 1).

The present status of gravity-surveys in this country is shown in Figure 2, wherein the preponderance of stations along the Atlantic and Gulf coasts is especially striking. A large proportion of these stations has been determined within the last five years. Many of them are distributed along nearly straight lines instead of over areas, and it will be noted that several of the lines are at right-angles to the structural trend or coast-line. This method of distribution has been experimental so as to gain information regarding the optimum spacing between stations, in order that all gravity-data pertinent to general geodetic purposes can be secured by occupation of a minimum number of gravity-stations. It has thus been found that the best spacing of stations along gravity-profiles is from five to ten miles, though a smaller spacing may be desirable in an occasional critical area, and a wider spacing may be quite sufficient in other places.

Figures 3 to 5 show in somewhat greater detail the gravity-surveys already completed along the Atlantic Coast. Southern New England and the adjoining part of New York have been fairly well covered with a combination of scattered stations and profile-lines. With the exception of the stations in and around Rhode Island, which were determined at the request of Charles Brown, most of the New England work was carried out in cooperation with Chester R. Longwell of Yale University, who has already reported on his interpretation of the results in a paper read before the Section of Geodesy of the American Geophysical Union in April, 1938.

The remainder of the stations shown in Figure 3 have been determined in cooperation with various organizations; notably, Lehigh University, the New Jersey Department of Conservation and Development, Princeton University, the United States Geological Survey, and the American Geophysical Union.

The two profiles across New Jersey follow the seismic profiles determined by Ewing and Woollard, and will be discussed later. The north-and-south profile through Bethlehem, Pennsylvania, was found to have the stations more closely spaced than is necessary, especially in an

area of this sort. It has served to show, however, what results may be expected from this type of intensive survey, and what the desirable spacing of stations may be in areas where gradients are not particularly steep. As will be emphasized by G. P. Woollard's map, the very pronounced zone of large negative anomalies which extends from Lake Champlain southward past Hagerstown, Maryland, is strikingly expressed in the Bethlehem profile.

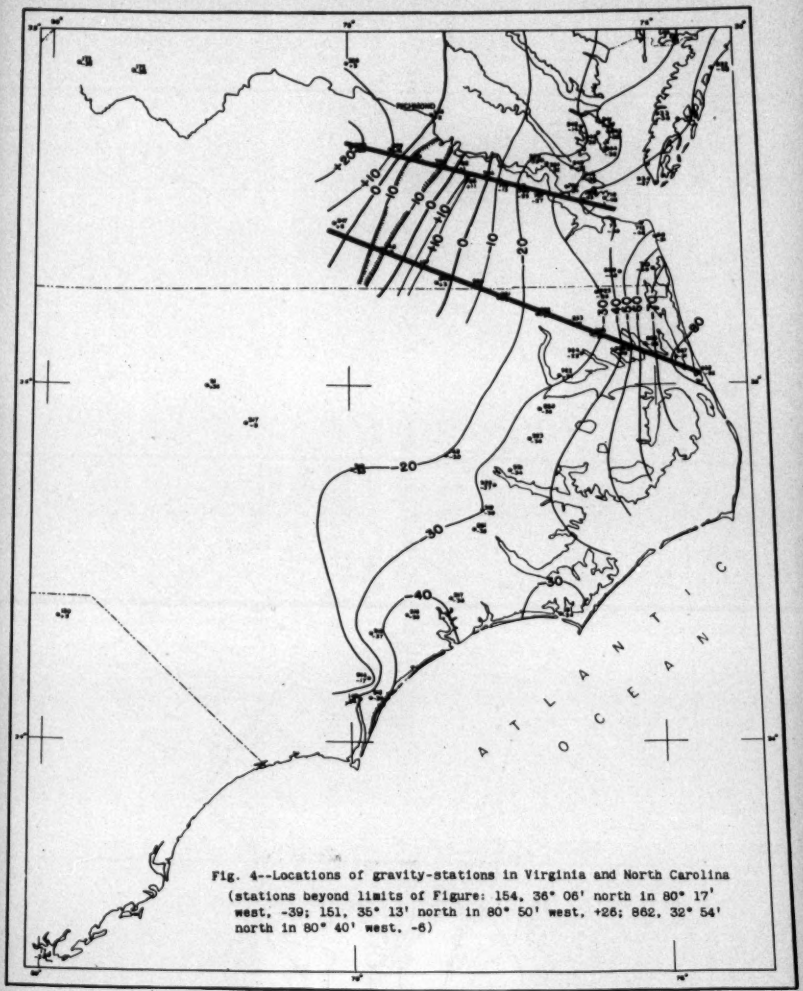
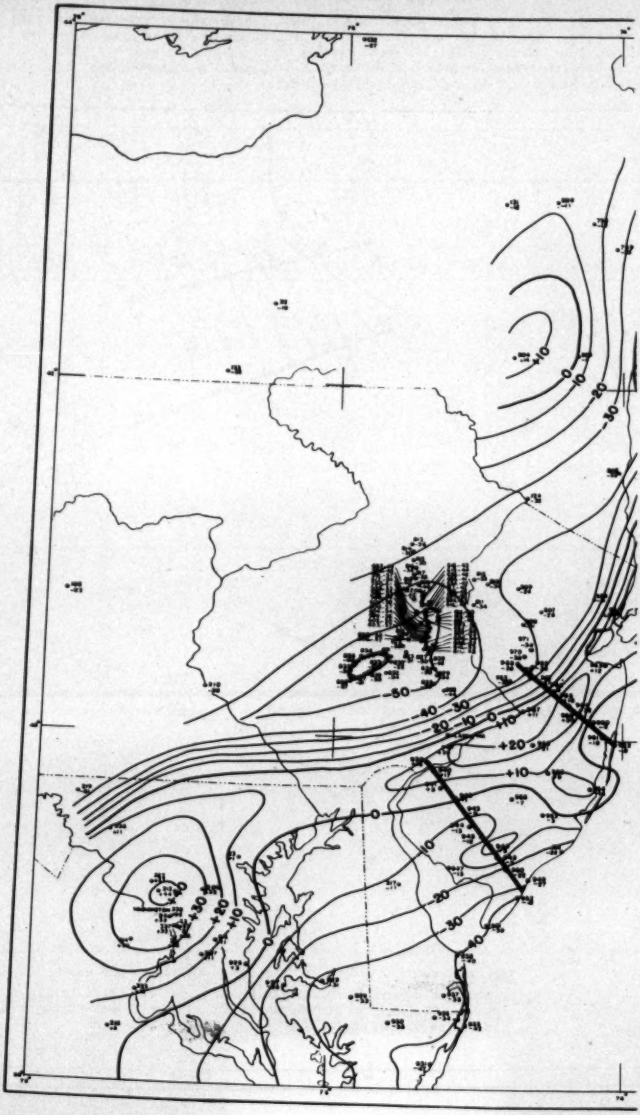


Fig. 4--Locations of gravity-stations in Virginia and North Carolina (stations beyond limits of Figure: 154, 36° 06' north in 80° 17' west, -39; 151, 35° 13' north in 80° 50' west, +26; 862, 32° 54' north in 80° 40' west, -6)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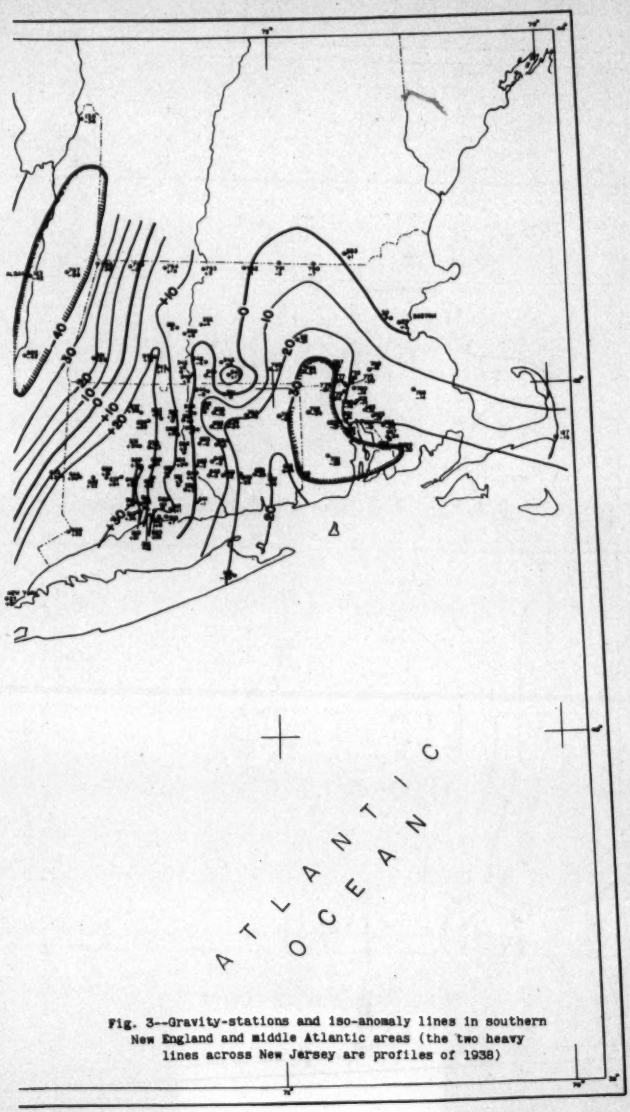

Fig. 3--Gravity-stations and iso-anomaly lines in southern New England and middle Atlantic areas (the two heavy lines across New Jersey are profiles of 1938)

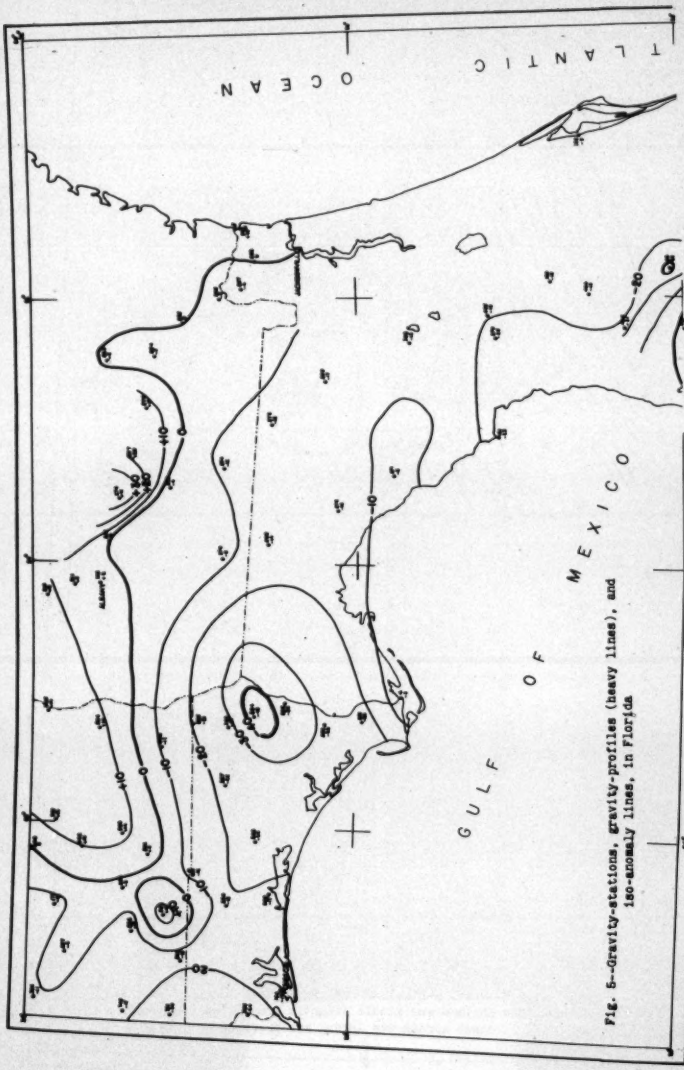

Fig. 5--Gravity-stations, gravity-profiles (heavy lines), and iso-anomaly lines, in Florida

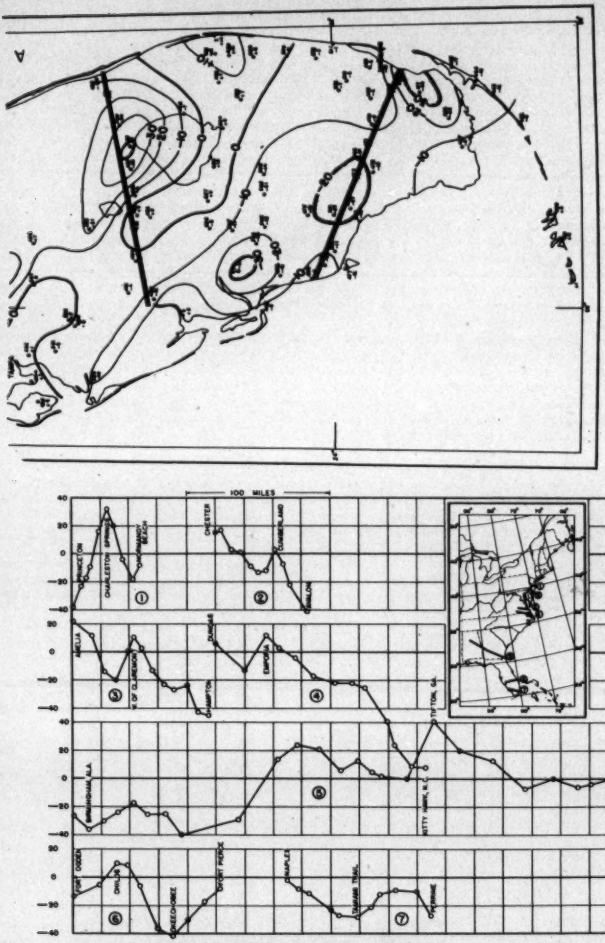

Fig. 6--Gravity-profiles after isostatic reduction (insert shows locations of profiles)

Most of the work in Virginia and North Carolina shown in Figure 4 was done in cooperation with B. L. Miller and Maurice Ewing of Lehigh University, and with Wilbur A. Nelson of the University of Virginia. The upper line of stations practically coincides with Ewing's seismic profile completed a few years ago. Of special interest are the steepness of the gradient toward the eastern end of the North Carolina profile, the very strong negative of 82 milligals at Kitty Hawk, and the break in the gradient about a hundred miles back from the coast. These are more

apparent in Figure 6. To explain the steepness of the gradient in the Hatteras area solely on the basis of a local deficiency of mass in the near-surface sediments, requires the assumption of an almost impossibly low specific gravity for these sediments.

In any attempt to explain a large anomaly such as the one at Kitty Hawk, it must be remembered that it takes a layer of normal surface-rock 30 feet thick and of indefinite horizontal extent to cause an attraction of one milligal. An anomaly of 82 therefore corresponds to the attraction (or rather lack of attraction in this case) of about 2,500 feet of surface-rock. When such a load, positive or negative, is assumed to be distributed as a variation from normal density, the dimensions of the mass and the percentage of departure from normal become very large.

The gravity-stations shown in Figure 5 are nearly all of them recent. About 50 of them in Northern Florida and in Southern Alabama and Georgia were determined early in 1938 in cooperation with the State Geological Surveys of the three States concerned. The results of this work may give some indication of the location of the buried extension of the Appalachians, in case this extension bends in the direction of Florida or the Atlantic Coast; but no indication of a structural transformation of the kind required is indicated by the results so far obtained. Interpretation of the results in this area by the State Geologists will, however, be greatly aided by the known logs of several deep wells near which gravity-stations were purposely placed.

The most interesting thing about the results in Southern Florida is the size of the anomalies in an area of practically no visible topography. The anomalies, or at least the gradients that they represent, must be due entirely to underground structure, as there are no corrections for either near-by topography or compensation, and the effect of the distant topography and compensation is nearly the same for each of these closely grouped stations. The consistent and definite trend of the anomaly-lines in a northwest and southeast direction across this part of the State shows the probable trend of the underground structure.

The data are shown in Figure 6 in somewhat different form. The locations of the seven profiles are indicated by numbered lines on the small insert, in the upper right-hand corner. I wish to call attention to a few of the principal characteristics of these profiles. The sharp peak at Charleston Springs, southeast of Princeton, New Jersey, is very striking (see Profile 1, Fig. 6). The change from an anomaly of -38 to one of +32 in only 25 miles approaches the steepest gradient (at Seattle, Washington) thus far found in the United States. The downward slope toward the coast is also quite pronounced in both of the New Jersey profiles. Farther south, the two profiles in southeastern Virginia and northeastern North Carolina (Profiles 3 and 4, Fig. 6) are found to be nearly identical. They, too, have a decided downward slope toward the coast. The sharp break about 100 miles back from the coast is apparent in both of them.

At the southern end of the Appalachians, the long profile from Birmingham to the coast is quite different from the others. It starts low in the mountains, rises to a moderate high in the Coastal Plain and then has only a very slight slope near the coast. The two profiles in Southern Florida show principally what has already been pointed out, namely, rather strong gradients in very flat topography. The low point north of Lake Okeechobee is especially noteworthy.

I have here attempted, very briefly, to show how gravity-determinations, reduced by the isostatic method, reveal significant variations in the character (and hence of the specific gravity) of different rock-masses far down within the basement-complex. It can readily be seen, however, that many more stations are needed before we can obtain a true picture of the mass and gravity-gradient variations in this area. The United States Coast and Geodetic Survey is anxious to carry the necessary gravity-work forward as rapidly as possible.

U. S. Coast and Geodetic Survey,
Washington, D. C.

GRAVITATIONAL DETERMINATION OF DEEP-SEATED CRUSTAL STRUCTURE OF CONTINENTAL BORDERS (STRUCTURAL INTERPRETATION OF GRAVITY-OBSERVATIONS)

George Prior Woollard

Introduction

Even though the composition and structure of the "basement-complex" is a matter of great interest to geologists, the determination of the constitution of the crust at depth can only in the rarest instances be accomplished directly by geological means. It must, therefore, usually

be accomplished by exploratory extrapolation, geophysically speaking, from regions of known surface or near-surface geology. Among the geophysical-exploratory techniques which may be used in this downward extrapolation of the structure and composition of the crust, the gravitational methods are among the easiest to use, are relatively cheap, and reveal highly significant anomalies, gradients, and patterns in the Earth's gravitational field. It has long been known that certain broad correlations exist between such gravity-anomalies and patterns, and deep-seated geologic structure; but until recently it was not feasible to secure gravity-measurements with sufficient accuracy and in sufficient abundance to do more than provide a basis for proving or disproving particular interpretations.

However, through the skill and activity of the companies which have been engaged in the exploration for oil, especially in the Gulf Coastal Plain, it is now possible to obtain gravity-measurements with such great precision that the local presence of both piercement and deep-seated salt-intrusions can be detected. Such work can now also be done quite rapidly. Furthermore, through the cooperation of the United States Coast and Geodetic Survey, it has recently been possible, as has just been indicated by Mr. Swick, to obtain profiles of closely spaced pendulum-stations, which not only prove that pendulum-measurements are indeed truly necessary controls for geodetic and engineering work, but also show that they can be made to give highly significant indications as to the structure and composition of the Earth's crust, down to depths of a number of miles.

As might be expected, the geological controls which induce the observable gravity-anomalies appear to be of different kinds in different regions. For example, in parts of the Rocky Mountains and in some of the African Rift Valleys, the gravity-anomaly patterns which have been found are apparently related to the rate of slope, and depth of burial beneath light sedimentary material of the surface of the denser basement-crystallines [see 1 of "References" at end of paper]--whereas, in New England, in the Atlantic Coastal Plain, and in the Piedmont (see Fig. 1) the gravity-anomalies now available indicate that the regional gravity-field is here disturbed partly as the result of compositional differences in the deep-seated portion of the basement-crystalline rocks--partly as the result of thickness variations in the light sediments overlying the basement eastward from the Fall Line, and largely as the result of regional geologic structural patterns which have been produced by orogenic crumplings and warpings of the Earth's crust, and especially of its lower surface. In this respect, the gravity-patterns now found to exist in the eastern United States seem to show interesting similarities to those discovered by Vening Meinesz and others in the course of their recent explorations in island-arc areas [2]. The current gravity-studies in the eastern United States, and companion studies which have recently been executed by the Royal Dominion Observatory at Ottawa, are, therefore, adding an interesting new chapter in the demonstration of how the structure and composition of the deeper parts of the Earth's crust may be deduced from detailed gravity and seismic profiles, and from regional gravity-anomaly data.

Relation of gravity-anomalies to regional geologic structure in the Eastern United States

The general gravitational net of the United States Coast and Geodetic Survey, the profiles described by Mr. Swick, the Gulf Research and Development Company's [3] gravimeter-traverse from Pittsburgh to Washington and Baltimore, and two of Dr. Vening Meinesz's trans-Atlantic gravity-profiles have provided data upon which Figure 1 of this paper has been based. The Figure has been derived by superposition of an iso-anomaly contour-map upon the Geologic Map of the United States, and it demonstrates:

(1) The presence of a zone or "strip" of fairly large negative anomalies paralleling the present western margin of the basement-crystallines, which have been thrust obliquely upward and northwestward against, and above, the rumpled Paleozoic strata occupying the Appalachian geosynclinal trough.

(2) The presence of a zone of fairly large positive anomalies (within the western New England metamorphic belt [4], and within the Piedmont area of basement-rock outcrop) which parallels the negative anomaly strip of (1), and passes between the Triassic fault-blocks, which tilt respectively eastward, and westward, away from this "gravity-anticline." This zone would seem to be analogous to the Hidden Range of Central India [5].

(3) The presence of another zone of fairly large negative anomalies in eastern New England, essentially parallel to the axis of the Naragansett structural trough or basin.

(4) The presence of minor "gravity-anticlines" and "gravity-synclines" in the Atlantic Coastal Plain, in the Allegheny plateau-region, and in Florida.

(5) The presence of a major "gravity-trough" or "negative-anomaly strip" in southern Louisiana, which apparently marks the present position of the axis of the Gulf Coast Geosyncline [6].

(6) The (presumptive) presence of a major transcurrent fault in the basement-rocks--crossing northern Florida, southern Alabama and Mississippi, and separating the Appalachian structural-and-gravitational province from that of the Florida and Gulf Coast region.

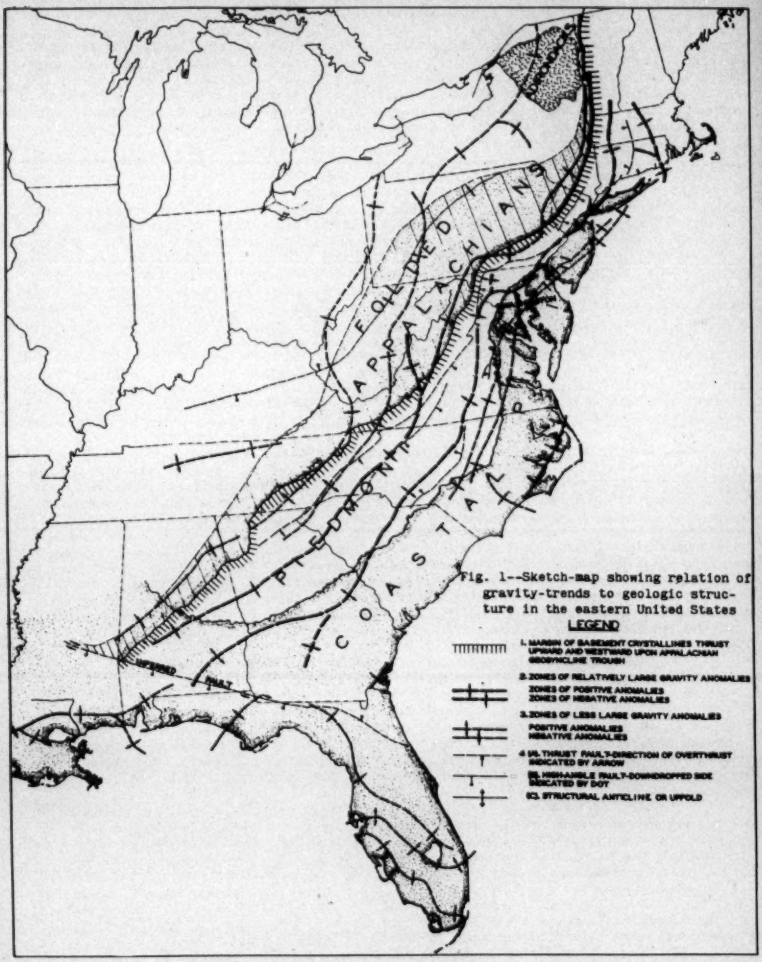
APPALACHIANS
FOLDED
PIEDMONT
COASTAL
PLAIN
LEGEND
1. MARGIN OF BASEMENT CRYSTALLINES THRUST UPWARD AND WESTWARD UPON APPALACHIAN GEOSYNCLINE TROUGH
2. ZONES OF RELATIVELY LARGE GRAVITY ANOMALIES
ZONES OF POSITIVE ANOMALIES
ZONES OF NEGATIVE ANOMALIES
3. ZONES OF LESS LARGE GRAVITY ANOMALIES
POSITIVE ANOMALIES
NEGATIVE ANOMALIES
4. (4L THRUST FAULT, T-DIRECTION OF OVERTHRUST INDICATED BY ARROW
(4L NORMAL(?) FAULT, T-DOWNDROPPED SIDE INDICATED BY DOT
(4). STRUCTURAL ANTICLINE OR UPFOLD

Fig. 1--Sketch-map showing relation of gravity-trends to geologic structure in the eastern United States

Relation of gravity-anomalies to lithologic variations in the basement-complex

As mentioned under (4), definite "gravity troughs and ridges" are present in the Atlantic Coastal Plain from North Carolina to New Jersey; but, as demonstrated by the work of Ewing and his colleagues [7], these are not descriptive of topographic irregularities on the surface of the basement-crystallines, but must be related to density-variations within the basement-rocks

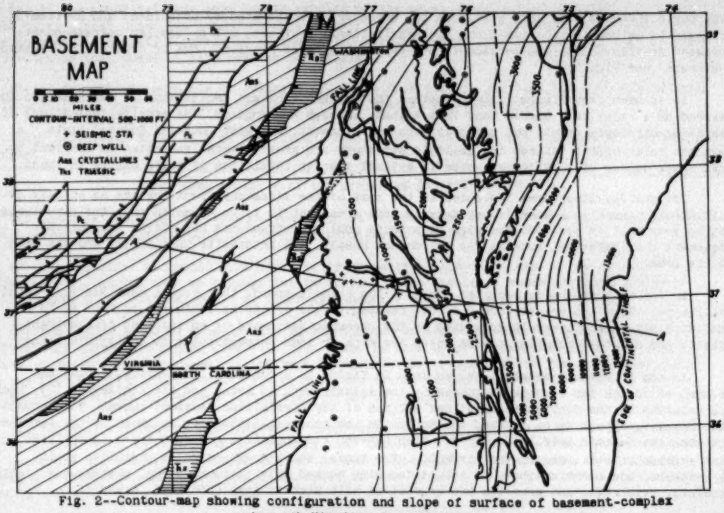

Fig. 2--Contour-map showing configuration and slope of surface of basement-complex beneath Virginia Coastal Plain

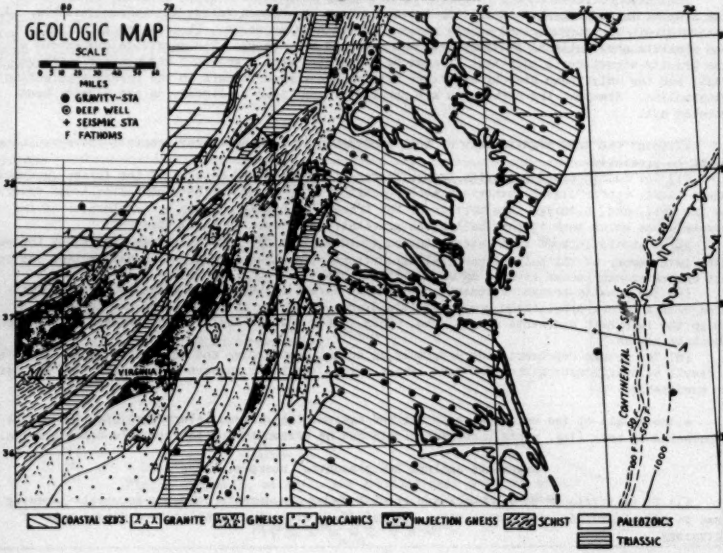

Fig. 3--Areal geologic sketch-map of Virginia

The correctness of this interpretation is, moreover, corroborated by coincident and systematic changes in seismic velocities along the gravitational profiles, and by similar correspondence between gravity-values and subjacent rock-types within the Piedmont area of crystalline-basement outcrops (see Fig. 2).

It is seen from Figure 1 that, whereas the surface-geologic indications of the Appalachians extend as a relatively narrow band from Alabama through New England, the gravity-indications of parallel structure extend out not only into the Piedmont, but also into the Coastal Plain. A genetic relationship between the geologic structure and gravitational variation is manifest by the close degree of parallelism which is evident even in localities of sharp change in trend.

The gravity-structures indicated to the west of the Allegheny Front are not so clearly delineated as there is a scarcity of data in this area; but it is to be noted that the structures agree very well in position and sign with those geologic structures reflecting crystalline-basement configuration, such as the Adirondack Massif, the Anthracite Coal Basin, and the Nashville Dome.

In the south there is a marked break in the anomaly-trends that occurs near the Gulf Coast Fall Line. That the gravity-break is not related to the onlapping sediments so much as to a definite structural break is suggested by the presence southward of an inferred transcurrent fault, and by other parallel trends which are more or less perpendicular to the Appalachians.

In the Atlantic Coastal Plain, as seen in Figure 2, occur parallel gravity troughs and ridges which, as has been demonstrated by the seismic work of Ewing and his colleagues [7], bear no relation to the configuration of the surface of the crystalline basement-rocks. The anomalies do, however, appear to be related to changes in the basement-lithology, as shown by the agreement between the seismic profiles. The relation between the anomalies and rock-types is verified in the exposed crystallines of the Piedmont. The dense, heavy rocks--such as injection gneiss, greenstone, and hornblendite--are associated with marked gravitational highs, whereas the lighter schists, rhyolites, and granites are associated with gravity lows (see Figs. 3 and 4).

That such surface-density relations do not apply to all the region, however, is shown by the area of marked negative anomalies, extending from the Hudson Valley to Alabama (see Fig. 1), for this belt is characterized at the surface by the heavier rocks. It constitutes a distinct and separate gravitational province from the one just considered. The magnitude and extent of the gravity-structure is such that it must be associated with a geologic structure of similar size, and the only known near-by structure meeting these requirements is the former Appalachian geosyncline. However, the structures are parallel rather than co-linear, as has already been pointed out.

Although the true significance of this phenomenon is unknown, three possible interpretations might be presented:

(1) The Hudson-Reading gravity-trough represents the eastern portion of the former geosyncline, where light, coarse clastic materials were deposited in contrast to the denser limestones observed to the west; and, although this portion of the trough has become covered by overthrusts of the crystallines which mask it physically, the gravitational effect is still apparent.

An alternate form of this interpretation would be that the gravity-trough represents the western twin member of the pair of parallel depositional troughs observed in the New England region, but one which has become covered by an overthrust sheet.

(2) The gravity-trough represents the remnant effect of the down-buckled tectogene associated with a former Appalachian system of island-arcs which lay to the east of the foredeep in which the Paleozoic sediments accumulated. This latter feature would be the present Appalachian Mountain region.

(3) The trough represents the effect of an actual downwarping and thickening of the crust as a result of overthrusting from the east, which forced the lower western member down into the heavier substratum.

Although all of the evidence, both for and against the various interpretations, can not be considered at this time, certain pertinent data can be presented for the reader's consideration.

Arguments against the presented interpretations

(1) It is difficult to visualize any great body of low-density, clastic material--assuming that it did accumulate--persisting since the Paleozoic without alteration to a denser type of lithology.

(2) If the anomaly-trough were due to warping of the crust under the depositional basin, it should carry across under the limestone area rather than stop at its edge, for even though the limestones have a density slightly in excess of the average crust, they are markedly lighter than the substratum that would be displaced by downwarping.

(3) If the anomaly were due to downwarping, it is difficult to see how it could persist without isostatic compensation being accomplished in the time-interval involved.

Other objections might also be raised, but the three stated above are regarded as the most important.

Arguments in favor of the presented interpretations

(1) There is accumulating evidence that much of the Piedmont area involves Paleozoic deposits, which may be altered only in the upper portions by overthrusting.

(2) The Paleozoic sediments were supplied by an eastern land-mass, and if the present coastal deposits can be used as a gauge for thickness, there should be somewhere much greater clastic deposits of lower Paleozoic or older age than are seen in the present sections.

(3) The Appalachians do show arcuate patterns, such as also characterize the "strips" of gravitational maxima and minima (see Fig. 1). Also, in harmony with observations on the peculiarities of island-arc structures, is the belt of marked overthrusts between the postulated foredeep and the tectogene gravity-axis; the belt of associated serpentines, and the line of Paleozoic volcanic activity which lies to the east of the tectogene gravity-axis.

(4) There is evidence of post-Paleozoic compressive stresses that could either preserve or produce the existing gravity-picture, assuming that compensation had been accomplished on Paleozoic materials and structures. These are the forces of the Appalachian orogeny, the Triassic arching and faulting, and present-day diastrophic stresses which give rise to the seismic activity in this region.

Of these forces, only those of the Appalachian orogeny appear to have been of sufficient magnitude to create the anomaly by a thickening of the crust through overthrusting. The lesser forces, however, may well have aided in preserving the original anomaly-condition or even in magnifying it. This possibility also holds for those interpretations which postulate downbuckling and warping of the crust.

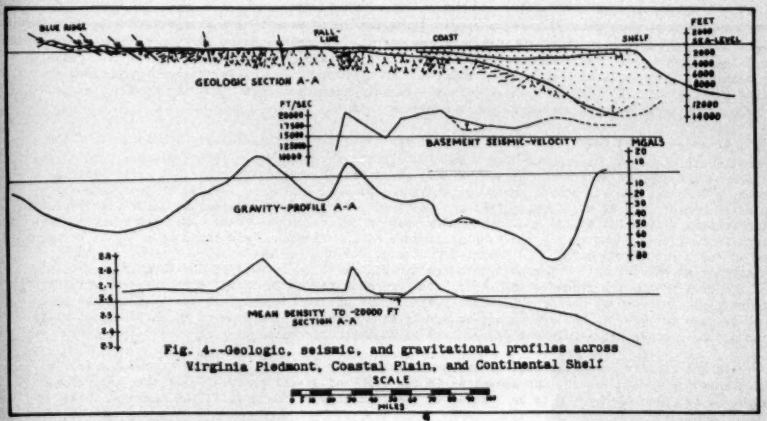

Fig. 4--Geologic, seismic, and gravitational profiles across Virginia Piedmont, Coastal Plain, and Continental Shelf

Gravity-sections

That the Triassic fault-basins and sediments of themselves play no important part in the anomalies was first pointed out by Longwell [4] in New England, and this is further shown by a comparison of the areal geology of Figure 3 with the sections of Figure 4. In no case is there any direct relation indicated between the gravity and any of the Triassic basins.

The only fixed relation to surface-geologic structural phenomena is that the main Hudson-Reading gravity-trough (see Fig. 1) underlies that region to the east of the Blue Ridge Mountains which is characterized by overthrust-faults. The trend is such that the axis of the gravity-trough lies on the eastern border of the overthrust-zone in the south and is practically co-linear with the main thrusts in the north. This relation is shown in Figure 3, which compares the trends of the gravity and known geologic structures. Also of interest in this connection is the relation of the gravity-trough axis to lines connecting seismic eipcenters in this region.

To the east of that portion of the Virginia Coastal Plain in which seismic-velocity correlations with the gravity-anomalies were noted, lies another marked negative anomaly-strip. It has been previously assumed that the increasingly large negative anomalies encountered in progressing seaward were due to the increasing thickness of the low-density sediments present. However, Swick has shown that only about one-third of the observed anomaly can be accounted for by the thickness of sediments at the Virginia coast, using the actual depth of sediments (see Fig. 2) and their determined density in the correction. Neither can the residual anomaly be attributed to the lithology of the basement-crystallines, for the seismic-velocity data indicate crystallines with a normal density of 2.67. It appears, therefore, that the marked anomaly-values along the edge of the Coast must be due to some other cause--perhaps deep-seated crustal warping.

That another explanation may be available is suggested by the anomaly-values established by Dr. Vening Meinesz off Hampton Roads, Virginia. These values, taken at the edge of the Continental Shelf, show that the gravity-structure near Cape Henry is a very sharp trough, presumably with a northeastward trend. As to what the control may be, such a sharp gravity-structure is in doubt, and the writer would prefer (in the light of the present meager data) merely to call attention to it rather than try to interpret it. However, the possibility that this "anomaly-strip" may be related to an eastward thinning of the continental crust, rather than a warping in connection with the sedimentary load, should be pointed out. This interpretation is supported by the fact that the axis of the gravity-trough lies back of the axis of the crystalline-surface warp, as outlined by the seismic-depth determinations in the district. Additional data will be required to check the existing indications, but present data suggest that there might be density-transition in the crust at the continental border, traceable to changes in the relative amounts of acidic and basic crustal material composing the geologic column.

Conclusions

From the general gravity-picture presented, which includes all of the available data thus far obtained, it is seen that the anomalies demonstrate the existence of certain systematic gravitational structures. These structures near the eastern seaboard appear to bear a genetic relationship to the Appalachian Mountain system; and in the Gulf Coast region appear to run more or less perpendicular to the Appalachian trends--probably being separated from the Appalachian province by an inferred northwestward-trending basement-fault.

Although in the south it is impossible to say exactly what the geologic counterpart of the anomaly-structure is, on account of the masking effect of the Coastal Plain sediments, it is possible in the east to make a comparison between the Appalachians and the adjacent gravity-strips. Here, all of the gravity-strips, even out under the Coastal Plain, as well as in the Piedmont, parallel the trends of the Appalachians and, with the exception of the smaller structures beneath the Coastal Plain, all of the gravity-zones appear to be continuous ones. There is a marked western anomaly-trough underlying the overthrust-zone of the Piedmont, and its origin may be explained in any one of three ways: (1) A buried trough of low-density material; (2) a downbuckled tectogene associated with a former island-arc structure; (3) a downwarped and thickened section of the crust resulting from overthrusting. In reference to the last two, more or less continual conditions of stress in the crust, as indicated by the geologic history of the area and the present seismic activity in the overthrust-zone, may have preserved the present anomaly-belt as relics and may have prevented attainment of complete isostatic compensation.

In the area lying to the east of the negative-anomaly belt and extending across the Fall Line into the Coastal Plain, the anomalies in the light of direct observational data and seismic-velocity correlations appear to be related to the lithology of the crystalline basement-rocks,

and are dominated by a zone of large positive anomalies extending from western New England to Alabama.

In the coastal and off-shore area extending out to the edge of the Continental Shelf, the anomalies indicate the presence of a marked eastern negative-anomaly zone which, when corrected for the sediments present, can not be attributed to their mass, but rather must be related either to a downwarping of the crust or to some continental border-line phenomenon as yet imperfectly understood.

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THE SEISMIC DETERMINATION OF DEEP-SEATED CRUSTAL STRUCTURE IN CALIFORNIA

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The determination of deep-seated geologic structure from the study of earthquakes has much in common with the determinations made of more shallow structure by the seismographic refraction-method of prospecting. But the earthquake solution presents more difficulties. (1) We do not know just where earthquakes will originate. Therefore, we must build seismographic stations scattered throughout the domain to be investigated. These stations are expensive to establish and maintain, and, since the results of the investigations are not of any obvious economic value, the funds to support the stations are difficult to obtain. We cannot, therefore, have stations distributed every few miles from our sources. (2) We do not know when an earthquake will originate. Therefore, the stations must be kept in continuous operation with the resultant cost of maintenance and supplies. We cannot operate our recording drums at very high speeds (with resultant high accuracy in times measured), because of the expense of photographic paper for continuous operation.

When an earthquake is recorded, the first problem is to compute the position of its source and the time of its occurrence--data already in the hands of the seismic prospector when he attacks the problem of interpreting his seismograms. And our stations are not well distributed as are his, which are arranged to give maximum ease of interpretation. We can measure time to only tenths of seconds (and that only for the better stations), whereas he may obtain any division he desires. This means that he can detect smaller irregularities of structure than can we. We have more intense sources and hence deeper penetrations; therefore, we can detect larger features on a rougher scale.

Another difficulty which we face is that we cannot arrange to have less sensitive instruments near our source and more sensitive instruments at larger distances from our source. Therefore, a shock well recorded at some distance frequently gives a record so large that only the time of first beginning can be read on the seismograms of stations near the source.

The method of interpreting the layering of the Earth's surface by refraction-methods has grown out of travel-time curves (of the type given in Fig. 1), on which the arrival-time of longitudinal waves at each station is plotted against the distance of that station from the source. The overlapped portions of the curves may or may not be observed--that is, arrivals later than the first may or may not be measured. The linearity of the branches of the curve, based on observations in different directions from the source, leads to the conclusion that the Earth is horizontally layered, and that the first waves recorded at stations indicated on the different branches of the curve have traveled linear paths near the upper surfaces of the various layers. The physics of such a simple set-up is difficult, because by simple optics the amount of energy in the indirect waves is not explainable. However, we have at present some mathematical explanation of the phenomenon [see 1 of "References" at end of paper]. From a travel-time curve of the type of Figure 1, the depth of layers can readily be computed. As I understand it, the early refraction-prospectors used only the waves first arriving at each sta-

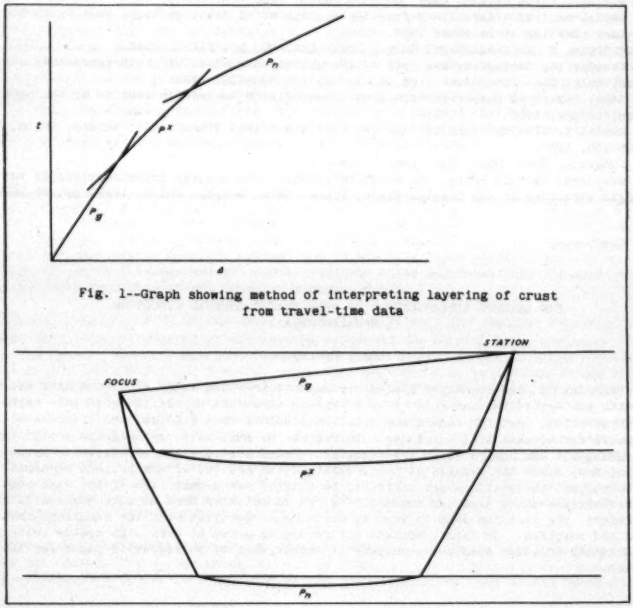


Fig. 1--Graph showing method of interpreting layering of crust from travel-time data

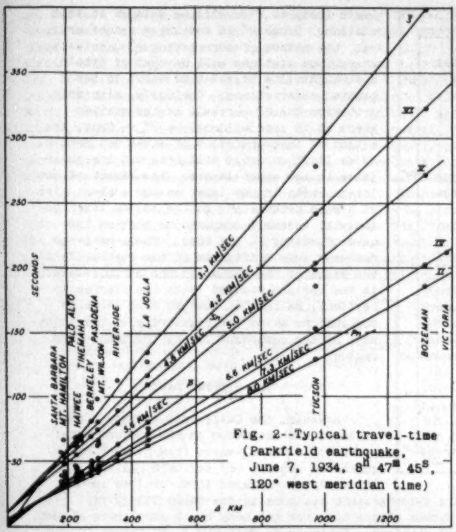


Fig. 2--Typical travel-time (Parkfield earthquake, June 7, 1934, $8^{h}\ 47^{m}\ 45^{s}$, 120° west meridian time)

tion for their curves. Since their receivers could be as closely spaced as desired, they were not compelled to lose any branches of the curve, unless the increase of velocity in successively lower layers was too small to allow a particular wave ever to emerge first.

But in earthquake research, the lack of closely spaced stations makes it almost impossible to observe as first arrivals any of the waves except $\overline{P}$ (or P_g)--that of the upper or "granitic" layer (speed 5.6 km/sec). Therefore, an interpretation of the subdivisions of the crust depends on the correlation at successive stations of groups of waves arriving after the beginning of the seismogram.

Now the first wave to record at any station, if it is well recorded, is unique and all will agree to its time to within certain very small limits of measuring error. But later arrivals are not unique in this way, and difficulties of interpretation enter. On the travel-time graph, we may least-square a straight line through the first arrivals in the region of each branch and get remarkable agreement. But the later arrivals plotted on the travel-time graph are always scattered; and, before one may least-square a curve through them, he must pick out the points on the graph which he intends to correlate at the different stations. He may draw few curves, allowing a wide scatter, or many, with a small scatter. He must look at the records of various stations and try to find some similarity of wave-form to help him, and this is very confusing. Figure 2 shows a typical travel-time graph.

Thus it can be seen how the subdivisions of the crust may be found as few or as many.

Studies of this sort from travel-time curves in California have led to the conclusions that the Earth's crust is there 30 to 40 km thick; that the surface-layer shows a speed of 5.6 km/sec and is less than 15 km thick; that under it and above the mantle are two or three layers [2].

As used in this paper, the Earth's crust is considered to consist of that upper 30 to 40 km of the Earth which seismological studies indicate is layered. The mantle is that portion of the Earth between this crust and the Earth's core at a depth of about 2,900 km. Whether or not the mantle is layered is not yet a matter of general agreement. If it is layered, the layers are very much thicker than those at the surface, the first marked change in the mantle being at a depth of 400 km.

To a geologist, a discussion of the "Earth's crust in California" as a unit with one set of values seems ridiculous. There is a reason for the regularity of the seismologist's structure. The bottom of the lowermost (seismic) surface-layer is shown by the seismological data to be at about the same depth in most parts of California where we have seismographic stations. An exception is under the southern high Sierra, as discussed below. This bottom of the crustal layers is identified by the arrival of the P_n-waves which travel just below it, and the data show by the accurate linearity of the travel-time curve (accurate to our limits of error which now lie usually under half a second) that this bottom varies very little in depth among our stations. More accurate data in the future may show slight variation. But our conclusions as to the average thickness of the various layers above are based primarily on the identification of waves traveling just under them and never recording as first arrivals on our records. If the granite-layer is much thicker under one station than at the others, the wave traveling just below the granite-

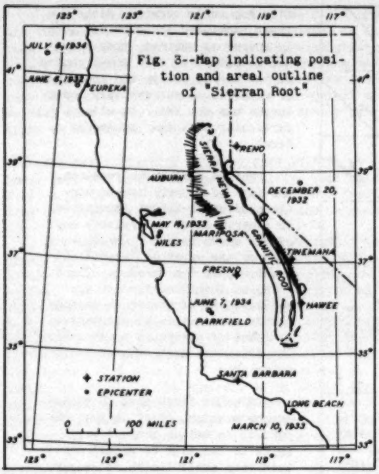


Fig. 3--Map indicating position and areal outline of "Sierran Root"

layer (call it P^*) will be delayed at that station. Since P^* is usually a second arrival, the method of correlating P^*-arrivals at various stations will be that of fitting a straight-line travel-time curve to the plotted observations. Obviously, with this criterion the P^*-arrival at the station where it is late will not be P^*. Thus, the method of interpretation of waves not recorded as first arrivals will iron out irregularities in the upper layers. The effect of the irregularity in any layer on the arrival-time of a wave penetrating to the second layer below will be small compared to that on the wave traveling at its base. Thus, while we can have some confidence in the regularity of the depth of the bottom of the surface-layers in the regions studied (with the Sierran exception), we can not have so much faith in conclusions as to the regularity of the thickness of the component layers throughout the region.

The Sierran root

However, the California picture offers at least one exception to the uniform interpretation. The P_n-waves from coastal earthquakes in central and northern California uniformly are delayed three or four seconds in their arrival at Tinemaha and Haiwee, the seismographic stations in the Owens Valley [3]. The arrival of P_n at Tinemaha and Haiwee from Nevada shocks and from the Long Beach shock have showed no delay. The delay is caused west of these stations. There is no delay of P_n to Fresno in the Great Valley from coastal shocks. Therefore, I have interpreted the delay observed in Owens Valley from coastal shocks as being caused by the root of the Sierra Nevada projecting below the general level of the bottom of crustal layers. Thus, Tinemaha and Haiwee lie in a shadow, and such P_n-waves as arrive at them have traveled a long way in the slow crustal layers of the mountain mass. Figures 3 and 4 show, respectively, the outline of the root at the base of the surface-layers as previously computed, and an idealized cross-section of the structure suggested. The northern boundary of the root cannot be delineated for lack of stations with accurate time-service in the lee of the mountain mass to the north. Professor A. C. Lawson [4] has considered in his isostatic computations that the whole Sierran mountain mass is granitic, and the outlines of the root as shown in Figure 3 have been computed on this basis. That the root may be made up of any or all of the surface-layers is not excluded by seismographic data, and I am still seeking information on this question. The difficulty is to determine whether or not waves of speeds typical of the intermediate layers are observed arriving on time from coastal foci to Tinemaha

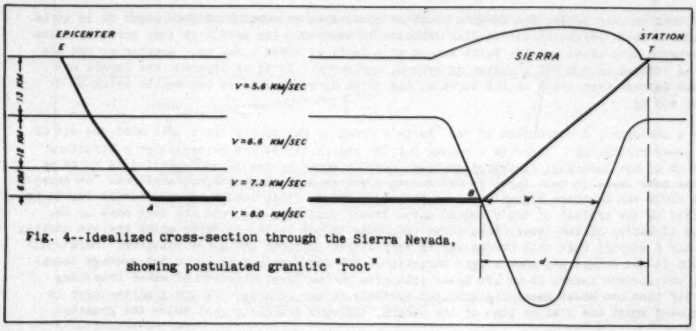


Fig. 4--Idealized cross-section through the Sierra Nevada, showing postulated granitic "root"

and Haiwee. Now as stated above, there are many later arrivals. It has been customary to correlate waves at different stations if their arrival-times at these stations, when plotted on a travel-time graph, lie on the same straight line, which line indicates a wave of "reasonable" speed. But if a given wave arrives regularly too late at a given station, there is grave danger that it will be correlated with a later wave at stations on normal structure. And I have almost despaired of correlating waves of near earthquakes at successive stations by distinctive waveforms. The waves all have too much in common in their appearance--crest followed by trough with some irregularity in superposition. This much, however, can be said for the possibility that the Sierran block is not all granite: it is frequently possible by the straight-line travel-time curve criterion to observe waves from the intermediate layers at Tinemaha and Haiwee undelayed. The earthquake which centered near Mina, Nevada, on December 20, 1932, was well recorded throughout the United States, and its epicenter was well located [5]. The P_n-waves from this shock showed no significant delay in their arrival at Santa Barbara, and these waves must have passed under the Sierran root in the vicinity of Haiwee and Tinemaha. However, both the epicenter and the Santa Barbara station are well away from the mountain mass, not in its lee as are Tinemaha and Haiwee for coastal shocks. I have least-squared the travel-time curve from the Nevada epicenter to the California stations and find no significant general curvature--no evidence of a generally curved path for P_n-waves dipping down that might miss the root. Considering possible errors in time of observation at Santa Barbara and a possible diffracted path under the root, it appears highly unlikely that the root could extend more than 40 km below the general level of the bottom of the crust--that is, more than 40 km into the Earth's mantle. It is very likely that the projection is considerably less than this.

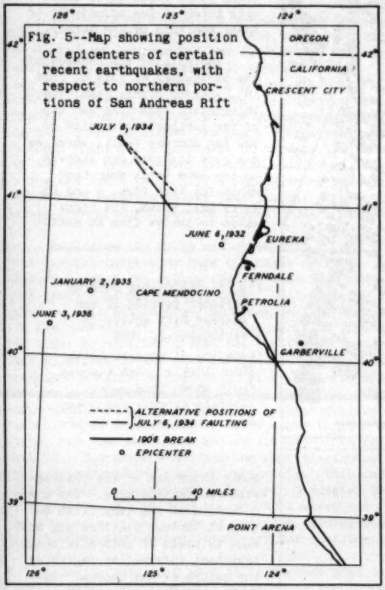


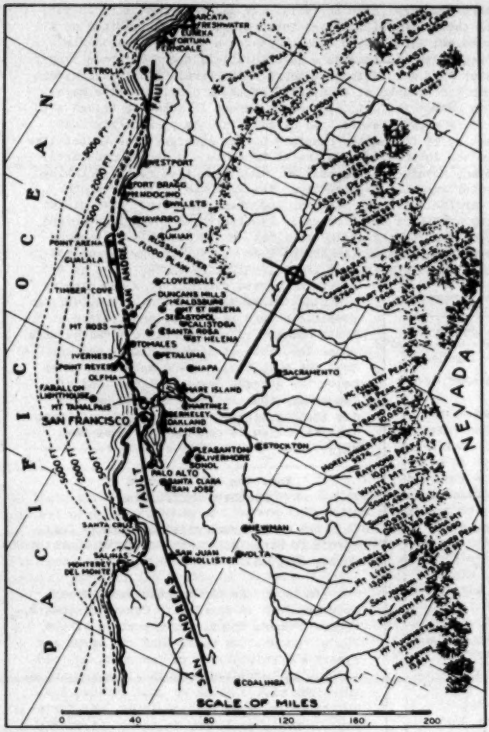
Fig. 5--Map showing position of epicenters of certain recent earthquakes, with respect to northern portions of San Andreas Rift

Faulting off the coast of Northern California

One of the most seismic areas in California is situated off the coast of Humboldt County (Fig. 5).

In 1906, the San Andreas Fault broke from San Juan in San Benito County northward. Figure 6 shows the northern portion of the fault. It will be noted that the break was almost a straight line as far north as Point Arena. As indicated in both Figures 5 and 6, there was also a break on land farther north in the vicinity of Petrolia near Cape Mendocino. On the fault-map in the Atlas of the Report of the State Earthquake Investigation Committee, this break was connected by a dotted line with the break at Point Arena, on the assumption that the fault followed on the sea-floor a course similar to that indicated by the dotted line. However, the fault-maps of the State issued since that mentioned above have ignored the break of 1906 near Petrolia, and some geologists have expressed the opinion that the San Andreas Fault probably extends to sea beyond Point Arena in approximately the same straight-line course which it follows to the south, and that the break of 1906 near Petrolia was merely a small break on a parallel fault. It has always interested me to locate accurately epicenters in the off-coast region to see if they tend to line up on a linear extension of the fault below Point Arena, or if some of them tend to fall on an extension of the Petrolia break.

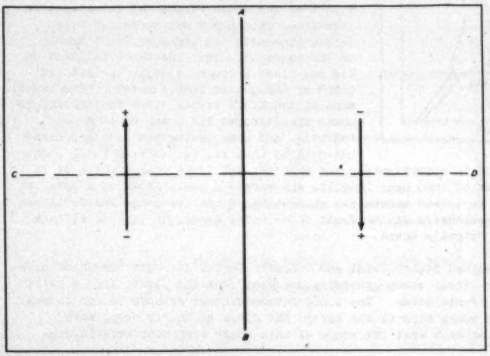
Recent depth-soundings of the United States Coast and Geodetic Survey off Cape Mendocino have led to the discovery of a remarkable linear scarp extending due west from the coast, from a point a little south of Cape Mendocino and Punta Gorda. The 1,000-fathom contour extends as far to sea as 125° 40'--over 100 km. The sharp scarp dips to the north, the slope southerly being more gradual. Unverified field-records indicate that the slope of this scarp over considerable dis-



tance is as great as 25 per cent. The distribution of the few epicenters very accurately located in this off-shore region renders it not unlikely that this is a fault-scarp which is still active. The same epicenters do not indicate a lining up along a linear extension of the Point Arena segment of the San Andreas Fault. But in approximately the locality where such an extension would cut the great submarine scarp, the unverified field-records of the soundings indicate a peculiarity in the contours which leads us to await with interest the adjustment of these contours by the Survey.

Analysis of the records of the earthquake of July 6, 1934 [6], yielded highly significant information regarding the dip of the northerly extension of the San Andreas Fault, where we now give the name San Andreas to the 1906 break near Cape Mendocino (see Figs. 5 and 6). As is well known, the first waves to arrive from an earth-

Fig. 6--Sketch-map showing northern portion of San Andreas Rift active in earthquake of 1906
(Location of damaged towns shown thus • ; San Andreas Fault shown thus ——; mountain-heights and ocean-depths indicated in feet)



quake-focus are of the compression-rarefaction type. The distribution of the very first motion at various stations may be made to yield in favorable cases important information regarding the nature of the source. Referring to Figure 7, if AB is the trace of a vertical fault which moves as indicated by the arrows, stations in the directions from the epicenter contained in the different quadrants may be expected to receive first P-motion as compression (+)

Fig. 7--Distribution of compressions and rarefactions for displacement along AB

or rarefactions (-) as indicated in the Figure. Since our stations are distributed over a Globe, it is possible by ascertaining the distribution of first compressions and first rarefactions widely over the Earth to determine the azimuth of the fault-trace. By the distribution of these motions, it is clear that one may not differentiate whether AB or CD (at right-angles to AB) is the fault-trace. But in the locality in question, namely, the epicenter of the earthquake of July 6, 1934, there is no doubt that the azimuth which gives the general azimuth of the San Andreas Fault farther south is the better one. The azimuth was determined as north 40° west from this shock. The dip of the fault may be determined from the same data. It was found that the fault dips about 84° northeasterly, that is, toward the Continent. The motion along the fault was shown by the same data to be northwesterly on the western (oceanward) side, and southeasterly on the eastern (continental) side, exactly as the historical movement of the fault farther south. The question may be asked, "At what depth is the dip of the fault 84°?", for some geologists feel that the dip of faults should vary with depth. I am sorry that I have no definite data as to the depth of focus of this shock, but I think that its source was below the surface-layers, because I detected no layer-waves at near stations. If this is correct, then the focus was at least 30 km deep, and the San Andreas Fault does not flatten appreciably to at least that depth.

There are no epicenters associated with the marked submarine canyon which soundings have shown off Monterey Bay. There are some epicenters in the Bay, but none off the coast. The lack of earthquake sources off the coast of California between the active region off Cape Mendocino and that off Point Arguello is very noticeable. It is notable that there are no earthquakes of any magnitude centering along the coast north of this area near Cape Mendocino until we come to the neighborhood of Queen Charlotte Island. Now the San Andreas Fault zone south of the Cape Mendocino region, as far as the Golden Gate, has been quiet since 1906, but at that time it was in this quiet zone that the fault-displacement was the greatest. This fact, together with the present comparative quietness of that portion of the fault along which the maximum displacement of the 1857 (Fort Tejon) earthquake occurred, suggests that the normal distribution of activity along the fault is that of a region where few but violent earthquakes occur, followed by one in which many moderate shocks take place. Maxwell Allen once pointed out this, drawing his conclusions from historic records alone. Modern seismographic observations check it.

Regarding the dying out of seismic activity northerly from Cape Mendocino, we might say that the coastal fault-zone hugs the coast northerly to Queen Charlotte Island, and that the lack of shocks between the Island and the Cape Mendocino Region is due to the fact that this is one of the fault's normally quiet zones. But since we have no authentic historic record of any great shock in the Washington-Oregon Region [7], this explanation is not good. It means a marked change in the behavior of the fault-zone north of Cape Mendocino over that observed throughout California. It might be considered that the fault-zone trends to sea northerly from Cape Mendocino, preserving the direction it has held through most of its course in central California. Under these circumstances, a large earthquake on it in historic time might have centered so far at sea from the Oregon-Washington coast as to have been only moderate in its intensity along the coast. But on this hypotnesis, if the fault is to preserve its characteristic behavior, we should expect another zone of moderate activity along it at a distance northwest of the Cape Mendocino zone of about the same magnitude as the distance from the Golden Gate to Cape Mendocino. No such region exists. Therefore, the faulting characteristics change definitely at the northern boundary of this Cape Mendocino zone of epicenters. This change is at a place where the linear zone of faulting reaches the continental border. I suggest that these two facts are intimately connected; that the faulting system dies out where it meets the Pacific structure. To the south of Point Arguello we find an east-west line of faulting causing some epicenters off the coast [8], but again these are bounded and are not found very far from the coast.

When I speak of a lack of epicenters some distance at sea in this region, some readers may recall that the epicenters published in the "International Summary" do not, perhaps, lead to this conclusion. I disregard these locations for the "Summary" does not pretend to be very accurate. For fifteen years I have been observing the records of shocks from this region. Previous to that the "International Summary" locations were very poor--for example, the "Summary" gave the location of the epicenter of the main Pleasant Valley, Nevada, shock (October 2, 1915), about 250 miles south of the region of faulting, and that of the big foreshock 300 miles southeast.

Summary

Seismographic data in California have led to the following conclusions regarding deep-seated structure:

(1) For the central and southern parts of the State, the average total thickness of the surface-layers (above the mantle) is 30 to 40 km with about 15 km of granite at the top and two or three layers below it.

(2) Under the southern part of the Sierra there is a root which does not extend out under the valley on either side, but only under the high part of the range. This root projects into the mantle, that is, below the surface-layers less than 40 km--probably considerably less.

(3) The San Andreas Fault extends north from where it broke in 1906 in Mendocino County at least as far as the epicenter of the earthquake of July 6, 1934 (see Fig. 5). In this region, it has a dip of about 84° at a depth of perhaps about 30 km.

(4) There is some indication that the submarine scarp extending west from Cape Mendocino is connected with an active fault.

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THE TIME-PROBLEM IN CONNECTION WITH THE GEOPHYSICAL STUDY OF CRUSTAL STRUCTURE

Harlan True Stetson

The concerted attack on the structural and dynamic conditions of the Earth's crust, by the various geophysical methods that have already been so ably described, suggests the desirability of searching for possible extra-terrestrial forces that may induce certain crustal movements, for which there appears to be accumulating evidence.

Periodic or secular variations in geographic coordinates of any occupied station should afford a source of data which may be of inestimable value in geodetic and geophysical research. The theoretical tide in the Earth produced through the gravitational attractions of the Sun and the Moon may introduce lateral and vertical movements periodic with the variations in the tidal potential. It would appear that such small variations as must exist in the coordinates of the station are perhaps of the order of magnitude that could now be detected by the best geodetic and astronomical measurements. Analyses of long series of variations in latitude have already suggested a certain dependence of such variations upon the hour-angle of the Moon, and there is some evidence, although often conflicting, that seismic disturbances are most frequent at preferential positions of our satellite.

The question of measuring earth-tides resolves itself, on the one hand, into measurements of a very small rise and fall of the crust as a function of the vertical component of the lunar tidal force, and on the other hand, the measurement of small horizontal displacements as a function of the tangential component of this same luni-tidal force.

Were it possible to measure both these components with the requisite precision, we might expect to find under normal conditions a difference in phase-angle in maximum displacement in the two respective cases of some 45°.

Preliminary experimental results from the Gulf Research Laboratories two years ago rather definitely indicated that the sensitive gravimeter developed at that Laboratory in Pittsburgh

was sufficiently precise to record the rise and fall of the crustal structure with the changing hour-angle of the Sun and Moon. It would appear, therefore, that the precision of gravimeters is now sufficiently great to offer an answer to the geophysicist's prayer for detecting and ultimately measuring small periodic changes of geotidal origin in the vertical direction.

The problem of determining small movements in the direction of the horizontal component caused by extraneous disturbing forces over the Atlantic Ocean resolves itself into determining with high precision longitude-differences on the two sides of the Atlantic. While the actual linear displacements caused by diurnal variations in gravitational potential of the Sun and Moon are known to be small, any secular changes in potential which may result may well be within the limits of observations now capable of being made. Extensive study of small variations in longitude made in recent years gives some promise indeed that we are nearing the degree of precision which geophysicists may hope will yield the kind of data desired.

The rather startling variation in longitude amounting to some 20 meters in mid-latitudes, first announced by Dr. Loomis and myself at a meeting of this Association in Atlantic City in 1932, has been found to be involved with an annular term introduced by a seasonal shift in the accepted system of geographical coordinates caused by the small motion of the pole of the Earth's axis of rotation that has long been recognized as the principal cause for the Chandlerian period of latitude-variation. Although such an annular variation exists without adequate explanation, there still remains the problem of determining the magnitude of the diurnal or semidiurnal changes in longitude that theoretically exist. A re-examination of data previously used, together with the analysis of three additional years of observation heretofore unpublished, suggests a diurnal and semidiurnal crustal tide of about one-quarter the magnitude we were first led to postulate.

More recently investigations elsewhere have shown variations in longitude which appear to correlate with the Moon's position. Observers at Zi-ka-wei in Shanghai, China, have published data indicating apparent variations of as much as 20 meters difference between Berlin and Shanghai. Japanese observers have found apparent variations in longitude as determined by a comparison of time-signals although not of so large an order of magnitude. An investigation of long series of data of latitude-determinations made with the zenith-telescope at Greenwich and an analysis of observations made with the photographic zenith-tube at Washington have revealed small changes that may be attributable to Earth-tides, but of an order of magnitude consistent with anticipated values.

It appears conceivable that an analysis of many years' observations would reveal such amplitudes and variations as persist in a definite fixed period. There may be irregularities over shorter intervals as would be the case were there intermittent translational movements under accumulated stress. The problem is of sufficient interest to merit further investigation. It should be emphasized that any increase in the precision of time-determinations and the communication of time by radio, places in the hands of the geophysicist improved means of investigating variations in geographic coordinates quite independent of triangulations on the Earth's crust itself.

The problem of measuring differences in longitude with sufficient precision to detect horizontal displacements under such conditions involves two operations: (1) The determination of the exact time of transits of stars across the meridians of Greenwich and Washington, respectively, with the highest attainable accuracy; (2) the communication of these times by radio to each of the stations occupied.

As has been pointed out by Mr. Loomis and myself in the two papers on the subject, which have already appeared [see 1, 2 of "References" at end of paper], evaluation of small changes in longitude rests upon the fundamental assumption that radio waves conveying the time-signals pass with the same velocity whether traveling with or against the rotation of the Earth--an assumption which, at least for low-frequency waves such as were used in our analysis of the Rugby-Annapolis signals, would appear to be justified.

That we have found evidence that the effective velocity of radio transmission is not the same as that of light, and that the velocity may vary with geomagnetic latitude and with the season, is a fact which, of itself, does not immediately enter into the question now under discussion [3]. Whatever the velocity and path taken by the waves of propagation between Washington and Rugby, we need only suppose that the path and the velocity are the same from west to east as from east to west, in attacking the problem of variations in longitude

Since, however, no longitude-determination can be more precise than the trustworthiness of the constancy of radio-wave propagation in both directions at the moment of comparing time-signals, it is highly desirable that such a fundamental supposition should be tested by experimental methods

before adopting without question any results dependent upon time-signal comparisons. A project has therefore been submitted to and approved by the Planning and Projects Committee of the American Geophysical Union that we believe will afford at least a preliminary test of the validity of this fundamental assumption.

The precision obtained by Ewing [4] in making gravity-determinations at sea, where the timing mechanism of the pendulum-apparatus was a crystal-chronometer constructed by the Bell Telephone Laboratories and loaned to the American Geophysical Union, led us to believe that this time-piece could be profitably employed in testing the fundamental assumption relative to the propagation of time-signals by radio. This project proposes, therefore, to transport by airplane a crystal-chronometer capable of maintaining a rate within $0^s.001$ per day from Langley Field near the Naval Observatory in Washington to a point in the interior of the country some 2,000 miles west of Washington, the plane to fly at a speed of approximately 200 miles per hour, and to record aboard the plane the Washington signals as received by the crystal-chronometer. Similarly, signals from the moving chronometer would be recorded at the Naval Observatory. Since these time-signals will be received hourly, there should be an apparent cumulative lag in the reception-times of about $0^s.001$ for each successive hour of flight. Assuming that a continuous flight of seven hours can be made before the termination of the journey, there will be an accumulated lag of $0^s.007$ by the time the signals are received over the 1,400-mile base-line--a time considerably in excess of any expected error of which the crystal-chronometer is capable.

In a return journey immediately following, the $0^s.007$-lag should be reduced by approximately $0^s.001$ per hour until arrival of the plane again at Langley Field in Washington. The crystal-chronometer originally synchronized with the crystal-clock at the Naval Observatory should again appear to be in complete synchronization at the end of the experiment. If the experiment performed as just outlined yields the consistent results anticipated, we should, we believe, have sufficiently verified the fundamental assumption as to the constancy of east-to-west and west-to-east transmission of wireless waves, thus removing all shadow of a doubt as to the trustworthiness of data dependent upon time-signal communication. Should there appear a difference in the lag of the reception of the signals in the return journey from corresponding signals received on the out-going trip, we should probably have made an even more significant contribution to science than the expected results would have presupposed.

With the present precision of star-observations by modern photographic methods, and the precision in time-keeping now attainable through the invention of the crystal-clock and the crystal-chronometer, we have available astronomical tools of much significance to geodesy and geophysics. Then it would appear abundantly worth while to provide and analyze longitude-determinations with a view to the geophysical significance of such data in the attack on problems concerned with the geologic structure of continents and ocean-basins.

Such fundamental problems in geology as have been discussed in this symposium emphasize what science may hope to gain through the coordination of some of its various branches in the attack on a single problem. Through the cooperation of astronomy, geodesy, and geophysics in a well-coordinated plan, we may hope to attain results that could not so well be brought about through isolated efforts in one or more of the technically specialized fields independently considered.

References

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OPPORTUNITIES FOR COLLABORATIVE RESEARCH IN FURTHER STUDY OF CONTINENTAL BORDERS

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The regions around the borders of our existing continents are, indeed, areas of especial interest and importance to Earth-science--both because of the major geological problems of these particular areas themselves, and because it is across these thresholds that our explorations of the ocean-basins must be chiefly projected. For example: Do the steeper, outer slopes of the various continental shelves actually mark the margins of definite continental "blocks," or are they the scarps of great faults, along which "founderings" of the oceanward crustal segments have occurred? Or are these outer slopes merely the fore-fronts of compound submarine deltas, which are extra loads, resting upon a crust which extends continuously from continental upland to ocean-floor?

Have mountain ranges tended to develop along continental margins, either because of "continental drift," or because of intercompetition between "suboceanic and subcontinental wedges"? Or do shore-lines (on subsided continental margins) merely tend to follow the trends of pre-existent mountain ranges? Are submarine canyons (such as are now known to notch the margins of the continental shelves) not only traceable landward into definite river-valleys, such as those of the Hudson and Congo, but also outward, onto and across the present ocean-floor--thereby reasonably indicating former emergences of the floors of the deep oceans? Can gravitational patterns, such as were shown by Figure 1 of Dr. Woollard's paper, be duplicated for suboceanic regions, and can such patterns be interpreted in terms of crustal structure in the light of the marine gravity-studies which have been executed by Vening Meinesz, Vening Meinesz and Wright; Vening Meinesz and Hess; and Ewing, Hoskinson, and Hess? If so, it should, perhaps, be possible to make an indirect, but nevertheless real, demonstration that the Appalachian fault-and-fold system of America not only extends eastward beneath the North Atlantic, but is, in fact, continuous with the Hercynian mountain system of western Europe.

Can we, by expansion of our seismographic observatories, not only determine the nature of the major faulting now in progress in coastal and suboceanic regions, but also obtain positive proof that most (if not all) mountain ranges have real "roots" composed of downward bulges of the lighter crustal materials? And can we develop a network of astronomic observatories, which will make exact stellar observations and also exchange radio time-signals, so as to reveal the exact motions imparted to the Earth's crust by extra-terrestrial forces and influences? [For a continued series of such observations should provide a sound basis for explaining the great (relative) lateral shifts of the crust--such as have occurred during the production of the world's mountain systems--and such as are now in progress within some of the Earth's major seismic zones.]

The problems which I have just mentioned are of such character as to indicate that opportunities exist for an almost limitless number and variety of useful researches, and the nature of most of these needed studies is also obviously such as to call for broad cooperation, both between individuals, between institutions, and between nations.

Moreover--as Professor Longwell has pointed out in his introductory paper--it is now realized that subsurface exploration must proceed from the known to the unknown, from the surface down, and from the simple to the complex. Hence it is obvious why the exploratory attention of those interested in the Earth's structure has been centered upon continental border-areas, and why we are anxious to cross the "bridges from the subcontinental to the suboceanic" which are provided by the world's continental margins. That these "bridges" now lie open before us has, furthermore, been indicated by the speakers who have followed Professor Longwell.

That marine sounding and positioning are now so skilfully done as to permit of the making of accurate topographic maps of the ocean-floor was shown by the paper of Doctor Veatch and Lieutenant Smith. That the topographic surfaces of former continental areas can be traced with approximate accuracy and in some detail, beneath a cover of mantling sediments and beneath the ocean, has been demonstrated by Professors Nelson and Ewing. That gravitational and seismic methods can be used for learning much about the structural make-up and dynamics of the deeper crust, has been shown by Mr. Swick, Dr. Woollard, and Professor Byerly. And that we may soon be able to test the possible efficacy of cosmic forces in producing terrestrial deformations has been pointed out by Doctor Stetson. These facts and ideas come as confirmations and extensions of the work and writings of many men--and are particularly convincing indications of the importance of the experimental investigations and researches which have been fostered by executives of various important companies actively interested in the discovery and development of mineral resources (ores, petroleum, non-metallics, underground waters, and the like). Such applied-science

research in petroleum and mining geology and, more particularly, in "exploration-geophysics" has indeed made amazing contributions to current and future general geophysical-geological research, both through the perfection of new methods and instruments, and through the accumulation of quantitative data.

What we need next in the further study of continental borders, and in the extension of such work into the ocean-basins proper, can be covered by a single summary statement: We need a great deal more topographic, geophysical, and geologic surveying of our continental shelves, and of their seaward margins, using: (a) Modern geodetic and acoustic instruments for locating local submarine topographic details; (b) the Piggott gun, or similar devices, for securing samples of the near-surface sediments; (c) modern seismic equipment for determining the rate, direction of slope, and probable character of the basement-rocks, and, so far as possible, of the overlying sedimentary formations; and (d) modern gravitational and magnetic instruments--and additional seismograph stations--for determining the structure and present dynamic activity of the deeper crust, both on land and at sea.

Such studies can be carried forward to excellent advantage across the Gulf Coastal Plain, along the Pacific border of the United States and Alaska, along the Atlantic margin of the United States, and in comparable areas throughout the world.

The opportunities for collaborative effort in the study of continental borders are therefore practically infinite in number, and the chief requirements for further success in this interesting and useful line of endeavor will be the desire to cooperate, the capacity to plan, and the ability to accomplish, efficiently and economically--without haste, and also without delay--on the part of the large groups of men necessarily involved by such an undertaking.

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Editorial note: While not presented in the Symposium, reference may be made to the paper by N. H. Heck on "Earthquake problems of the Atlantic Coastal Plain," which was delivered at the morning session of Section E of the American Association for the Advancement of Science, December 27, 1938. It is published in the Bulletin of the Seismological Society of America [v. 30, pp. 109-113, 1940].

[Note: For index of names and of subjects in Part III-A, see page 1056 and following.]